Southeastern Geology: Volume 3, No. 3
February 1962

Edited by: E. Willard Berry & S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

J. R. Butler

Southeastern Geology

VOL. 3 NO. 3

FEBRUARY, 1962

SOUTHEASTERN GEOLOGY
PUBLISHED QUARTERLY BY THE
DEPARTMENT OF GEOLOGY
DUKE UNIVERSITY

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SOUTHEASTERN GEOLOGY

Table of Contents

Vol. 3, No. 3

1962

A REVIEW OF REGIONAL HEAVY-MINERAL RECONNAISSANCE AND ITS APPLICATION IN THE SOUTHEASTERN PIEDMONT *

by

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ABSTRACT

Heavy-mineral reconnaissance is a method of regional geochemical exploration particularly adapted to humid temperate and humid tropic areas where surface exposures of rocks are deeply weathered. It consists of measuring the abundance and distribution of heavy minerals, mainly detrital grains in stream sediments, relating the findings to regional geology, and delineating favorable areas for further detailed search.

Results of the method are rather coarse grained, but they can define geochemical provinces and broad anomalies within the provinces. Heavy-mineral reconnaissance is best adapted to regional surveys containing at least several thousand square miles with sample intervals of one sample per 2 to 4 square miles.

The main ore minerals that have been located by the method are gold, platinum, monazite, thorite, thorianite, pyrochlore, chromite, ilmenite, rutile, diamond, columbite, tantalite, scheelite, wolframite, barite, and cassiterite. Combination of geochemical analyses of stream sediments with heavy-mineral reconnaissance extends the range of the exploration to the base metals.

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* Publication approved by the Director, U. S. Geological Survey.

Heavy-mineral reconnaissance is adapted from the ancient methods of stream prospecting. It was first employed in a systematic way in the 1880's by O. A. Derby in Brazil. In the early 1900's the method was used in successful surveys for cassiterite in Nigeria and thorite in Ceylon, and in the 1920's its use resulted in the discovery of diamond deposits in Sierra Leone and the Gold Coast. During the 1930's heavy-mineral reconnaissance was introduced in Russia to aid in regional appraisals of mineral resources. Heavy-mineral techniques were highly perfected in Madasgascar beginning in 1953, where as many as 13,000 concentrates were examined in a year in successful searches for thorianite, monazite, chromite, ilmenite, cassiterite, columbite, and pyrochlore.

Modern heavy-mineral reconnaissance was begun in the Southeastern Piedmont in 1935 by L. M. Prindle and W. A. White. They were followed in about 10 years by J. B. Mertie, Jr., of the U. S. Geological Survey, who pioneered an era of large regional heavy-mineral studies. Heavy-mineral reconnaissance in the Southeast since the 1940's by the Geological Survey has in part deciphered the geologic relations of monazite deposits in the Piedmont, delineated metamorphic zones in the western Piedmont, and begun to outline geochemical provinces favorable for tungsten, gold, and the base metals in the central Piedmont of North Carolina.

CONTENTS

TABLES

ILLUSTRATIONS

INTRODUCTION

Purpose

The purpose of this review is to bring together in one paper the very scattered references to heavy-mineral reconnaissance and to use them to trace the history of the development of the technique, describe methods, and illustrate its application in the Southeastern United States and elsewhere. Direct quotation from pertinent literature is used to make available many old and obscure references. Empirical solutions of problems associated with field aspects of heavy-mineral reconnaissance, such as size of the sample, density of the sample net, and sampling rates, are given from published accounts of successful surveys to show what has been done. Where the empirical solution might be improved, possible areas of inquiry are mentioned. The section describing work in the Southeastern States is a summary of the research conducted by the U. S. Geological Survey, and in part sponsored by the U. S. Atomic Energy Commission. Geochemical studies made by private companies are not reviewed, because little about the results has been published.

Four lines of geochemical study have been followed by the U. S. Geological Survey in the Southeastern States. In the order of their introduction to the area--which is also their historical order of development--they are: heavy-mineral reconnaissance, analyses of water, metals in alluvium, and trace elements in detrital magnetite. The purpose of the study by the Survey has been to define geochemical provinces (Hawkes, 1957, p. 237-238) in areas underlain by weathered rocks. New regional geologic syntheses that may derive from regional geochemical studies offer the possibility of a sounder basis for private exploration than is presently available. An example of a new regional geologic synthesis useful in the search for an ore mineral is described and illustrated with a summary of the geologic cycle of monazite. Preliminary results showing the remarkable relations of the regional variations in the abundances of the trace elements in detrital magnetite are given as an example of a method of potential value in areas underlain by weathered rocks.

Acknowledgements

The writer wishes to acknowledge his debt to Mr. J. B. Mertie, Jr., of the U. S. Geological Survey, who in 1942 introduced him to the study of detrital heavy minerals as a means of geologic prospecting and, since 1948, has successively guided and encouraged him in heavy-mineral reconnaissance in the Southeastern States. Associates on Survey projects in the Southeast are mentioned individually later in the text, but they are here thanked for their painstaking work in the panning, examining, and interpreting of more than 5,500 concentrates.

REGIONAL HEAVY-MINERAL RECONNAISSANCE

Heavy-mineral reconnaissance as a method of geochemical exploration consists of measuring the abundance and areal distribution of heavy minerals, relating the findings to regional geology, and using the findings to delineate the most favorable places for detailed search for ore deposits. It is an ancient technique that is now included in the modern methods of geochemical prospecting (Hawkes, 1957, p. 301-304). It is particularly adapted to humid temperate and humid tropic regions where the rocks are deeply weathered.

The term heavy mineral as used herein means a mineral whose specific gravity is greater than that of quartz and feldspar. Heavy minerals are commonly, but not exclusively, accessory minerals in sedimentary, igneous, and metamorphic rocks.

Most of the heavy minerals are unaffected by weathering and are more or less resistant to mechanical disintegration. They accumulate with the weathering products of the parent rocks and may be found in the thoroughly weathered rock (saprolite), in residual and colluvial soils, and in stream sediments.

Regional heavy-mineral reconnaissance is best related to drainage systems, because heavy minerals from a sample of alluvial gravel are representative of all the rocks in the drainage basin upstream from the sample. Heavy minerals from a net of drainage basins give excellent representation of a region. Heavy minerals from residual soil or saprolite represent only the immediate parent rock; hence, heavy-mineral reconnaissance based on these materials is necessarily restricted. However, both saprolite and alluvium have been successfully used in regional heavy-mineral reconnaissance studies.

The heavy minerals must be separated for study from a large bulk of rock-forming minerals and weathering products, principally quartz, feldspar, and clay. Common ways of separating heavy minerals from the rock-forming minerals take advantage of the difference in specific gravity between the two groups. In the field they can be separated by panning. In the laboratory the quartz and feldspar are ordinarily floated off in a liquid which has a specific gravity slightly greater than 2.7. Bromoform, $CHBr_3$, with a specific gravity of 2.89 at 10° C (Krumbein and Pettijohn, 1938, p. 321), may be used for this purpose. Indeed, its use is so common that some authors have defined a heavy mineral as one with a specific gravity greater than that of bromoform. Inasmuch as the term heavy mineral actually comes from a comparison among minerals rather than a comparison between minerals and a liquid, the writer prefers to regard heavy minerals as ones that exceed quartz and the feldspars in specific gravity.

If panning is used to separate the accessory from the rock-forming minerals, the panner shortly discovers that some accessory minerals do not separate from the quartz and feldspar as readily as other accessories. They tend in varying degrees to wash out of the pan along with the light minerals in the final stages of concentration.

This feature is often used by the panner to regulate the degree of concentration achieved and to reduce the loss of certain wanted minerals. Minerals intermediate in their panning characteristics between the heavy minerals and quartz and feldspar may be conveniently called semi-heavy minerals. They range in specific gravity from 2.7 to about 3.3. A list of semi-heavy and heavy minerals that have been reported in concentrates from the Carolina Piedmont is given in Table 1.

History of Development

The pioneer in heavy-mineral reconnaissance is Orville A. Derby whose principal work was done in Brazil. Derby introduced panning to the scientific public as a way to recover accessory heavy minerals from weathered and unweathered rocks (Derby, 1889, p. 109-113; 1891a, p. 198-206; 1891b, p. 308-311; 1897, p. 304-310; 1898, p. 187-192; 1899, p. 343-356; 1900a, p. 207-216; 1900b, p. 217-221; 1902, p. 211-212; and 1905, p. 163-165). He led in relating the heavy minerals in streams to their geologic provenance. The idea, of course, is as old as prospecting, and the scientific literature from antiquity onwards mentions it. Indeed, the term "black sand" was in accustomed use by 1810 when Thomas Thomson (1810, p. 98-105) published an analysis of some from the River Dee, but Derby recognized that in regions of profound weathering clues to the rocks were preserved in the black sand. The idea has been subsequently developed by Alfred Brammall (1928, p. 28-48), P. G. H. Boswell (1933, p. 47-59), and T. H. van Andel (1950, p. 58-124) in studies of the provenance of detrital minerals. Provenance of detrital minerals in tropical regions was again demonstrated by J. A. Richardson to have considerable economic value because (Richardson, 1939, p. 79-80): ". . . knowledge of the minerals typically associated with a valuable commodity such as gold or cassiterite facilitates the search for it."

The start of systematic heavy-mineral studies is sometimes said to be marked by the work of D. T. Day (1905, p. 15-24; 1907, p. 141-153) and Day and R. H. Richards (1906a, p. 150-164; 1906b, p. 1175-1258) on the composition of black sand concentrates from the Pacific slope of the United States. Day and Richards analyzed large samples of heavy minerals, several of which were carload lots of concentrate from placers, and they determined the identity and abundance of the minerals in the concentrates. However, the conceptual character of their work, as reflected in the reports, contains little that was new when it was undertaken.

Several years before Day and Richards published their accounts of the regional distribution of heavy minerals in the Pacific States, personnel of the Imperial Institute (London) had been systematically

Table 1. Specific gravities of minerals that have been reported in concentrates from the Carolina Piedmont.

Specific gravity	Mineral	Specific gravity	Mineral
2.54-2.57	microcline, orthoclase	4.3 -4.6	barite
2.60-2.76	plagioclase group	4.45-4.56	xenotime
2.63-2.80	beryl	4.5 -5.0	ilmenite
2.65-2.66	quartz	4.68-4.70	zircon
2.7 -3.1	biotite, muscovite, phlogopite	4.7 -4.8	molybdenite
2.8 -3.7	amphibole group, pyroxene group	4.8 -5.3	martite
2.98-3.20	tourmaline group	4.9 -5.3	hematite, monazite
3.0-4.26	wad, allanite (orthite)	4.95-5.10	pyrite
3.01-3.25	fluorite	5.17-5.18	magnetite
3.15-4.3	garnet group	5.19-5.40	thorite
3.16-3.20	andalusite	5.3 -7.3	columbite-tantalite
3.17-3.23	apatite	5.6 -5.8	fergusonite, samarskite
3.23-3.24	sillimanite	5.8 -6.1	schelite
3.25-3.5	epidote, zoisite	6.8 -7.1	cassiterite
3.26-3.36	dumortierite	7.0 -7.5	wolframite
3.27-3.37	olivine	7.4 -7.6	galena
3.3 -4.7	psilomelane	10.6	sperrylite
3.4 -3.6	piedmontite, titanite (sphene), topaz	14.0-19.0	platinum
3.5 -4.1	spinel, chrysoberyl	15.6-19.3	gold
3.51-3.52	diamond		
3.52-3.57	chloritoid		
3.56-3.67	kyanite		
3.65-3.77	staurolite		
3.87-4.08	brookite		
3.9 -4.1	corundum, sphalerite		
4.0 -4.6	gadolinite, gahnite		
4.1 -4.9	chromite		
4.18-5.2	rutile		

Principal source for minerals: Genth, F. A., 1891, The minerals of North Carolina: U. S. Geol. Survey Bull. 74, p. 5-119.

Specific gravities from: Dana, E. S., 1932, a textbook of mineralogy with an extended treatise on crystallography and physical mineralogy; 4th ed., rev. 2nd enl. by W. E. Ford: New York, John Wiley and Sons, Inc., p. 1-851.

panning concentrates in Nigeria and Ceylon. A progress report outlining the discovery of cassiterite in Nigeria was published by W. R. Dunstan in 1906 (p. 7-31). Systematic heavy-mineral reconnaissance in Ceylon up to 1910 included the examination of more than 500 concentrates resulting in the discovery of commercial deposits of monazite, thorite, and thorianite, and the first observation and description of the mineral thorianite. The reasons the Imperial Institute considered systematic study of heavy minerals as part of its development program in Ceylon were stated by W. R. Dunstan (1910, p. 3):

> "As experience has shown the importance of river sand as a source of thorium-bearing and other valuable minerals, and also as an index of the mineral wealth of the district comprised within the drainage area of the stream in whose bed it occurs, the surveyors collected a large number of concentrates from the alluvium of different localities. These were forwarded to the Imperial Institute for examination and report, and a great deal of valuable information has been obtained from investigations."

Extensive heavy-mineral sampling was employed during the early 1900's in Brazil by Ferdinand Freise (1910, p. 47-64) in a search for stream placers containing monazite. In the 1920's N. R. Junner (1943, p. 33; 1955, p. 345-346) successfully applied heavy-mineral reconnaissance in a search for diamonds in the Gold Coast and Sierra Leone.

Heavy-mineral reconnaissance was adopted in Russia during the early 1930's to aid in regional appraisals of mineral resources. By 1935 results of prospecting for cassiterite were published (Ginzburg, 1960, p. 178-179), and by 1939, when a heavy-mineral map of the central and southern Urals was being made, A. P. Sigov (1939, p. 6) was able to write:

> "As a rule, regional geological surveys of igneous terrane should be accompanied by heavy mineral surveys, to determine the economic possibilities of the region. Heavy mineral surveys are both faster and cheaper than drilling or underground work. In such work, studies of alluvium are usually most suitable."

Sigov's comment is neither new nor novel, being anticipated by 50 years in the work of O. A. Derby and by 30 years in that of the Imperial Institute, but it displays the awareness of the utility of heavy-mineral reconnaissance which has led to its extensive use in Russia.

Heavy-mineral reconnaissance was adopted locally in Sarawak (Wilford, 1953, p. 32-34) and regionally in Malaya (Fitch, 1952, p. 51-52) in the late 1940's. It had been used sporadically in Alaska for many years prior to a program of intensive sampling that was begun in 1945.

Heavy-mineral reconnaissance on a grand scale was introduced into Madagascar in 1954 by Henri Besaïrie (1955, p. 1-3). Some of the Russian interest in heavy-mineral prospecting was transplanted to China during the late 1950's. R. A. Khan Tahirkheli used heavy-mineral methods in reconnaissance for uraninite in the Himalaya and Karakoram Mountains of Pakistan during 1958-59 (Danilchik and Tahirkheli, 1959, p. 1-7).

Large surveys by heavy-mineral reconnaissance were not begun on a systematic basis in the Southeastern United States until the 1940's (Mertie, 1953, p. 1-3; Overstreet and Griffitts, 1955, p. 555; Overstreet, Theobald, Whitlow, and Stone, 1956, p. 692-694). The development of these studies is reviewed in a separate part of the text.

Review of Procedures

Panning

Use of the pan for the recovery of heavy minerals is quite ancient. It was used as long ago as 300 B. C. to separate grains of cinnabar from sand (Theobald, 1957, p. 2), and it is still the basic field method for heavy-mineral reconnaissance. O. A. Derby writes that he was introduced to the gold pan about 1889 by a prospector and engineer, John Gordon, who had discovered the monazite placers in Brazil. Derby's account of his first use of the pan shows how he shought to relate placer minerals to their source rocks (Derby, 1891a, p. 110):

> "As gneiss is the only rock that is at all abundant about Rio de Janeiro, it was natural to suppose that the mineral [monazite] so widely distributed in the sands might have come from that rock. About the same time Prince Pedro Augusto de Saxe Coburg Gotha discovered in an apatite-bearing streak of the gneiss of the Serra de Tijuca a minute yellow crystal with the physical aspect of monazite, but too small for chemical tests. This suggested the idea that, notwithstanding the small proportion of the mineral and the microscopic size of the grains, it was not altogether hopeless to look for it in the rock itself, while Mr. Gordon's method of concentration by panning was naturally suggested as the simplest and readiest mode of investigating the question. Under Mr. Gordon's instruction I soon acquired sufficient facility in the use of the pan to make a satisfactory concentration and with his aid some scores of tests have been made of the rocks in the vicinity of Rio and from about a dozen points in the provinces of Rio de Janeiro, Minas Geraes and São Paulo. When decomposed rock was obtainable the tests were made on this by washing a

quantity equal to a heaped double handfull, care being taken to obtain material decomposed in situ and carefully freed from any extraneous wash. Where decomposed material was not at hand pieces of sound rock were ground in a mortar, a fragment the size of a fist or even smaller proving sufficient for a satisfactory test."

Other geologists have also thought that the gold pan is the most convenient tool with which to obtain in the field the concentrates used as the basic unit on which measurements are made in a heavy-mineral reconnaissance. Methods used by the Gold Coast and Sierra Leone Surveys in taking 15,500 concentrates between 1913 and 1929 are described by N. R. Junner (1955, p. 345-346):

"In the early days of both Surveys when little was known of the mineral resources of the countries, the pan was used essentially for prospecting purposes. Some important economic results were obtained, notably the discovery of the Gold Coast and Sierra Leone diamond fields and alluvial gold and platinum deposits in Sierra Leone.

"As the work of the Surveys progressed from the reconnaissance stage to more detailed mapping, greater emphasis was placed on panning weathered rocks for geological information and especially for mapping geological boundaries. Routine testing of alluvials, eluvials and lode deposits by panning was continued, and special investigations were carried out, for example, sampling of andalusite deposits in weathered schists, pitting and loaming to locate the source of detrital gold and platinum occurrences, examinations of ores and mine tailings, and the determination of the size of gold in banket reefs.

"The heavy concentrates obtained by panning were examined and described in the field, and most of them were registered and kept for subsequent investigation or stored for future reference. A collection of them has recently been examined for radioactive minerals . . .

"The pan normally used in the Gold Coast and Sierra Leone was of 12 inch diameter, but a larger pan was employed for preliminary screening and puddling. Screens were used to separate fractions of different sizes and the panning was done, with the aid of a small panning stool, in a large enamel basin placed whenever possible on a level, dry spot in moderate sunlight. By these means a good deal of the back-breaking work of panning in a stream bed or a pool of water can be obviated and, what is more important, the panning can be more efficiently controlled. The above mentioned equipment, together with a pick and shovel, a 'dolly' pot and pestle for crushing hard samples, a nest of fine-mesh sieves and a few extra pans, can be readily transported."

Rates and Recovery. The rates at which sediments, crushed rock, and saprolite should be panned to insure a good recovery of minerals have been discussed by Frank Smithson (1930, p. 130-136), C. J. C. Ewing (1931, p. 136-140), Robert Peele and J. A. Church (1941, p. 10-537), J. B. Mertie, Jr. (1954, p. 647), and P. K. Theobald, Jr. (1957, p. 1-54). They show that minerals with high specific gravity like platinum and gold can be satisfactorily recovered from gravel at the rate of 6 minutes per pan. Minerals with specific gravity from that of garnet (3.5) to that of monazite (5.2) require slow and careful panning for good recovery. Mertie states that 20 to 30 minutes are needed to make a recovery of 80 to 90 percent of the heavy minerals in a pan of saprolite. Even longer time is needed to obtain the same recovery from a pan of crushed rock. Panning time for stream sediments is about the same as it is for saprolite.

Recovery of heavy minerals in panning has been discussed most recently and most thoroughly by P. K. Theobald, Jr. (1957, p. 21-22), who concludes:

". . . The average recoveries . . . in the . . . panning of riffle samples are:

Mineral	Recovery (percent)
Hematite	62
Ilmenite	64
Magnetite	59
Monazite	84
Rutile	68
Zircon	72

Special care must be taken with clay and silt. . . ."

Results of studies of recovery by panning with the "Asiatic ladle" were given by A. P. Sigov in 1939 (p. 3):

Mineral	Specific gravity	Coefficient of extration (percent)
Magnetite	5.2	90
Hematite, ilmenite, zircon	4.4-5.1	83
Garnet, corundum, rutile	3.9-4.2	76
Limonite, staurolite, kyanite	3.6-3.8	60
Not listed	2.8-3.3	15
Not listed	2.8	1

About 5 to 10 percent less monazite, rutile, and zircon, and 20 percent less ilmenite were recovered with the gold pan in the Southeastern Piedmont than with the "Asiatic ladle" in Russia. Probably these differences result from less efficient panning in the Piedmont where some ilmenite was deliberately washed out of the concentrate in the final cleaning. The deliberate removal of some ilmenite doubtless accounts in part for the concomitant lower recoveries of magnetite and hematite, but it seems quite likely that high losses for both these ores would have prevailed even if more ilmenite had been saved. Some of the magnetite and hematite consists of mere husks of grains, crumbly, porous, and hollow. Their effective specific gravity in panning is appreciably less than that of massive grains of the same mineral. High losses of magnetite and hematite represent a selective winnowing out of the hollow grains. In this regard it should be noted that the material classed as limonite by Sigov, and which may well be similar to some of the pseudomorphic grains called hematite in the Carolinas, has a coefficient of extraction of 60 percent in the "Asiatic ladle, " a recovery nearly identical to the recoveries of magnetite and hematite in the Carolinas.

Methods to be followed for good recovery in panning for diamonds were described by N. R. Junner in his discussion of the diamond deposits of Ghana, which were found by heavy-mineral reconnaissance. The immediate source of the diamonds is stream gravel which also contains, in approximate order of abundance (Junner, 1943, p. 21), staurolite, ilmenite, limonite, rutile, tourmaline, zircon, magnetite, hematite, leucoxene, kyanite, andalusite, and rarely, gold, amphiboles, sphene, epidote, monazite, garnet, apatite, corundum, sillimanite, beryl, and cassiterite. Junner states (1943, p. 33):

"Panning for diamonds has to be done slowly and carefully in a good light, preferably a strong diffused light, so that diamonds can readily be recognized by their brilliance and be picked out. Direct sunlight is unsatisfactory. Before being panned the gravel should be thoroughly washed and sized, and the panning must be interrupted at intervals, particularly in the late stages, to examine the gravel and concentrate for diamonds. If the pan is slightly greasy or if it is allowed to stand for a while and the bottom of it becomes partly dry, some of the diamonds present may float off on the water. This applies particularly to small and flat diamonds. To obviate this it is necessary to use a clean pan and when panning to agitate the water by an up and down movement of the hand."

J. B. Scrivenor published the results of experiments performed to test the recovery of sample washers who prepare cassiterite concentrates with a wooden pan known as a dulang. He writes (Scrivenor, 1911, p. 3):

"A Malay woman, Mak Siah, who had worked on the Gopeng Mines for fifteen years, and was stated to be very proficient, was selected for the trial, and she was asked to clean up four prepared samples, with the following results:

"Fifty grams of coarse cassiterite from Pusing Bahru were mixed with quartz-sand and earth. There was no amang* in the sample. Mak Siah's cleaned sample of cassiterite weighed 50.49 grams, the excess being due to impurities from the sand and earth that had not been pushed away.

"Fifteen grams of medium-grained ore were mixed with chalybite in small round grains, fine grained ilmenite, quartz-sand and earth. Mak Siah recovered a sample weighing 17.25 grams, the overweight being due to unseparated chalybite and ilmenite. It was found that she had saved all the cassiterite.

"Ten grams of cassiterite between 30 and 60 mesh were mixed with monazite, ilmenite, zircon, quartz-sand and earth. Mak Siah recovered a sample of the 4.9 grams only containing a considerable amount of zircon, monazite and ilmenite.

"As topaz is a nearly constant impurity in the Gopeng ores and has to be reckoned with in cleaning up prospecting samples, Mak Siah was asked to wash clean a sample consisting of nothing but grains of topaz and cassiterite obtained from the

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*Amang refers to the heavy minerals naturally associated with cassiterite and separated from it during cleaning. It is black sand tailings from cassiterite mines.

Chinchong rock in Pahang. In attempting to get rid of the topaz about 25 per cent of the cassiterite was lost."

A. F. Taggart (1947, p. 11-57) states that a skilled operator using a gold pan ". . . will make a lower grade of tailing on any ore amenable to gravity concentration than can be made in the most elaborate gravity mill. The concentrate will not, however, be of as high grade as can be made in a mill."

An area for research in the techniques of heavy-mineral reconnaissance would be an inquiry to discover if there are better field methods than panning to make the concentrate. Where the weight of the initial sample is 15 to 50 pounds, and where flexibility in the handling of diverse sample materials is needed, ready portability is wanted, and thorough cleaning between samples is desired, no field procedure is more satisfactory than panning. If very small samples can be shown to give representative concentrates, then it may be possible to develop a better method for the rapid concentration of a sample.

Size of Sample

The size of the sample depends on the purpose for which it is taken. Geologists in the Southeastern States have come to use larger samples than the double handful of saprolite or piece of fresh rock the size of a fist recommended by O. A. Derby (1891a, p. 110) from his experience in Brazil. J. B. Mertie, Jr., has taken samples of saprolite that weigh as much as several thousand pounds apiece, and the 516 samples he had panned by 1953 had an aggregate weight of 45,200 pounds (Mertie, 1953, p. 15). The writer and his associates took 15 to 25 pounds of saprolite at intervals of 0.2 to 0.5 mile in the Shelby quadrangle, N. C., and took 40 pounds (10 quarts) of riffle gravel at intervals of several miles in the Carolinas and Georgia. Herbert Yoho (1952, p. 239) used samples composed of about 10 pounds of rock fragments broken from different places on one outcrop. The largest samples taken by Mertie were exceptional in that they were collected to yield a gram of zircon, and the rock from which they came was unusually deficient in that mineral. Usually, however, representative heavy-mineral concentrates can be prepared from 10 to 25 pounds of saprolite, except from some schists and felsic tuffs in which the accessory minerals are so sparse that at least 50 pounds of saprolite is needed for usable concentrate. About 40 pounds of riffle gravel insures 20 to 200 grams of concentrate in most terrane underlain by pelitic schist, gneiss, migmatite, and granite. Areas underlain by slate and felsic volcanic rocks give about 2 to 20 grams of concentrate from a like size of riffle sample. Regions underlain by amphibolite, mafic schist and gneiss, diorite, gabbro, and syenite give about 200 to 2,000 grams of concentrate from 40 pounds of riffle gravel.

The optimum size of sample for systematic regional heavy-mineral reconnaissance has not been determined. The size obviously will vary with the requirements and the method of concentration. Any improvement in field procedures that would tend to reduce the size of the sample could speed the rate of the reconnaissance.

Density of the Sample Net

The density of the sample net depends on the purposes to be served by the samples and the scale of the reconnaissance. If the samples are from alluvium, and thus are tied to the regional drainage pattern, they can commonly be taken at wider intervals than samples taken from bedrock and still give equivalent representation. The literature discloses quite a variation in the density of samples in different investigations.

Ferdinand Freise (1910, p. 47-64) made a detailed study of stream placers in an area of one square degree in Minas Gerais and Expirito Santo, Brazil. Using local labor for drilling, test pitting, and panning, he took 6,238 concentrates from 1,553 pits and 1,801 boreholes. Thus the concentrates came from 3,354 localities in 1,100 square miles. The concentrates were analyzed with the petrographic microscope for 46 minerals, and the results were used to appraise monazite placers.

Personnel of the Service Geologique du Madagascar took 10 to 150 alluvial concentrates in geologic map areas of 250 to 1,000 square miles (Besairie, 1953, p. 1-154) in work prior to 1953. After that year they commenced a systematic program of heavy-mineral surveys focused on areas of about 800 to 1,900 square miles in which the geologists outlined mineralized tracts by collecting thousands of concentrates (Besairie, 1955, p. 1-3). From study of 13,000 concentrates commercial deposits of thorianite, monazite, ilmenite, and columbite were discovered. The sample intervals used in these surveys have been reported for two areas. In the Ankaizina district A. Emberger (1956, p. 53-54) collected 964 concentrates in an area of about 300 square miles. Detailed study of the concentrates disclosed local deposits of monazite, columbite, bauxite, beryl, and cassiterite. Jean Guigues (1955, p. 43) collected 2,800 concentrates to explore an area of 620 square miles in the Ampandramaika-Malakialina pegmatite district.

Members of the Geological Department of Mysore are reported (Memminger, 1917, p. 681) to have taken "many" heavy-mineral concentrates from streams, particularly in the Mysore charnockite district, in the opening years of the Indian monazite industry between 1911 and 1917.

The Geological Survey Department of the Federation of Malaya is said by F. H. Fitch (1952, p. 51-52) to emphasize the panning of sand from "all stream beds" in areas being geologically mapped. The primary object is to determine if gold or cassiterite is present. Fitch observes that examination of the concentrates yields other useful knowledge, and in his report on the geology and mineral resources of the Kuantan area, Pahang, he presents maps (Fitch, 1952, figs. 13-14) that show the parts of streams in which cassiterite, andalusite, and chiastolite occur. He also gives a map (Fitch, 1952, fig. 15) of an area underlain by sedimentary rocks intruded by a granite pluton. The map shows the association of garnet with cassiterite in concentrates derived from streams with drainage basins underlain by granite. No great number of samples was taken, but the details were worked out with concentrates representing individual drainage basins of 1 to 10 or more square miles.

Streams in special geological environments in Sarawak have been panned by members of the Geological Survey Department of the British Territories in Borneo (Wilford, 1953, p. 32-34; Haile, 1954, p. 36-37), but no regular regional sampling has been done. No fixed sample interval is used.

A. P. Sigov (1939, p. 6) states that in Russian practice "the density of the sampling net is determined by the scale of the map." The intervals suggested by Sigov amount to:

Scale of map	Square miles per sample
1:500,000	40 to 10
1:200,000	7 to 1.7
1:100,000	1.6 to 0.4
1: 50,000	0.4 and less

Samples of concentrates from streams in Alaska have been gathered by the U.S. Geological Survey since the late 1890's. Between 1945 and 1952 the collections were built to several thousand concentrates, and they were systematically examined for radioactive minerals. The sample net was related to geologic features, and the sample intervals were often rather close. Reports that discuss heavy-mineral concentrates in detail include pioneering work in the Chandalar region by J. B. Mertie, Jr. (1925, p. 263) and in the Rampart area by A. E. Waters, Jr. (1934, p. 239), and recent work on Baranof Island (West and Benson, 1955, p. 47-49), south-central Alaska (Bates and Wedow, 1953, p. 8-9; Robinson, Wedow, and Lyons, 1955, p. 5-7), east-central Alaska (Wedow, 1954, p. 6-9; Nelson, West, and Matzko, 1954, p. 11-15), and west-central Alaska (West, 1953, p. 2-7; Killeen and Ordway, 1955, p. 76-83; Bates and Wedow, 1953, p. 6).

Members of the U. S. Geological Survey's monazite placer reconnaissance project in the western Piedmont of the Carolinas and mapping projects around Shelby, Lexington, and Concord, N. C., have used a variety of sample nets. They have taken panned concentrates from saprolite or alluvium at intervals of 1 sample per 200 square feet, 10 samples per square mile, 4 samples per square mile, 1 sample per square mile, 1 sample per 2 square miles, and 1 sample per 4 square miles in various studies. Little or no improvement in geologic resolution was found beyond that obtained with 1 sample per square mile until the interval was reduced to a few 100 square feet. For reconnaissance where thousands of square miles should be examined to produce a broad picture, intervals of 1 sample per 1 to 4 square miles have proved to be satisfactory. These observations agree closely with those of Sigov (1939, p. 6).

The Geological Survey has also found that much useful data are shown when samples taken at intervals representing about 1 square mile are plotted at 1:24,000 and 1:62,500 scale. Any improvement in resolution seems to require smaller areas of representation than the 0.4 square mile suggested by Sigov for 1:50,000 scale.

The work of the Service Geologique du Madagascar in recent years shows a preference for 3 to 5 samples per square mile even where map scales as small as 1:200,000 are used. This frequency may actually be somewhat greater inasmuch as several samples may have been taken at each locality, but the literature is not clear on this point.

From these considerations it can be seen that Freise's sample net of 5 or 6 per square mile (2 localities per square mile) is a specialized exercise in placer appraisal, and that the density of 1 sample per 10 to 100 square miles used prior to 1953 in Madagascar deprives the samples of that degree of continuity among themselves requisite for regional geochemical purposes. Widely spaced alluvial concentrates are, however, useful adjuncts to petrographic descriptions and are indispensable for the discovery of sparse and inert accessory minerals. In this connection the geologically guided collections made from saprolite in the Southeastern United States by J. B. Mertie, Jr. (1953, pl. 1); from alluvium in Malaya by J. A. Richardson (1939, p. 79-81); from alluvium in Sarawak by G. E. Wilford (1953, p. 32-34) and by N. S. Haile (1954, p. 36-37) are models of heavy-mineral reconnaissance used as supplements to petrography. The immense number of concentrates taken in Madagascar since 1954 (Besairie, 1955, p. 1-3), in the Gold Coast and Sierra Leone (Junner, 1955, p. 345) in the 1920's, and in Nigeria and Ceylon between 1904-1910 (Dunstan, 1906, p. 7-31; 1910, p. 3) are the chief examples of systematic regional heavy-mineral reconnaissance except for those mentioned in Russia, Alaska, and the Carolinas. In these studies the density of the sampling net was modified to suit conditions and to suit the methods of presenting the results. From 5 samples per square mile to 1 sample per 40 square miles were used. Seemingly, 1 sample per 1 to 4 square miles is adequate for most regional reconnaissance, and in special circumstances of large areas and rugged country the interval can be increased to 1 sample in 10 to 20 square miles.

Sampling Rate

The number of concentrates panned per day varies with the type of material being panned, the size of the sample, the accessibility of the sample localities, and the proximity of water to the sample localities. As was previously stated the members of the Geological Survey's monazite placer project in the Southeastern Piedmont found that it took about 30 minutes to pan a standard sample of gravel weighing 40 pounds before sieving and 20 pounds after sieving. Standard samples of sand weighed 25 to 30 pounds after sieving and took 5 to 10 minutes longer to pan. Travel time between sample localities subtracts from the total time available for panning; thus the closer the net of roads the more sample localities can be reached in a day. On the placer project, most of the samples were taken within a few hundred feet of a road, and no sample was taken farther than a mile from a road. Water for panning was present at most of the sample localities; thus, nearly all the samples could be panned where they were dug. Under these ideal conditions an average of 10 concentrates per man per day was achieved for 4,200 concentrates panned.

The accessibility is poorer in the central Piedmont around Concord, N. C., than in the more heavily populated western Piedmont. Supplies of water at the sample localities are also not as good near Concord as in the western Piedmont; therefore, some samples had to be carried to satisfactory panning places. Lessened accessibility and fewer adequate panning places reduced the sampling rate of the Survey party in the Concord area to an average of 7 samples per man per day for 145 samples taken in 118 square miles.

Accessibility in the Slate Belt near Lexington, N. C., is about the same as it is in the central Piedmont, that is, about one sample locality in four is a quarter of a mile or more from the nearest road. Adequate panning places at the sample localities are uncommon, because most sample localities are the dry beds of intermittent streams. Under these conditions the samples of gravel are dry-screened at the locality and the minus one-eighth-inch sand is sacked and stored until enough samples are on hand for a full day of panning. An average of five samples per man per day has been reported in this area (A. A. Stromquist, written communication, 1960).

Sampling rates per man shown by A. P. Sigov for Russian field projects are seemingly lower than those attained in the Carolinas, but this is uncertain. He writes (Sigov, 1939, p. 6-7):

> "In 1936, an alluvial prospecting crew consisting of party chief, one washer, and two laborers, in a field season of 100 working days, did the following work:
>
> | Scale | Square km. area | Samples |
> |---|---|---|
> | 1:50,000 | 300 | 350-400 |
> | 1:200,000 | 1,500 | 300-350 |
>
> . . . Test pits were one to two meters deep, and two 30 kg. samples were taken from each pit. Production may be 20 to 30 percent lower in the event of difficult digging conditions, or unavailability of water for washing."

The rates cited by Sigov are said to be for a single party, but they seem to be averages from several, possibly many, field parties. He shows that four men collected 1,400 samples from 700 localities in 100 days at a rate of 3.5 samples per man per day. Evidently the washer did the panning at the rate of 14 samples per day, which is a greater rate than was attained by panners in the Southeastern Piedmont. The samples are 1.8 times heavier than samples taken by the U. S. Geological Survey in the Carolinas, and they were taken from pits, which were not used in the Carolinas. Inaccessibility probably reduced the sampling rate per man in the project described by Sigov.

The rates reported from the Carolinas come from three projects. After more experience is gained in heavy-mineral reconnaissance the sampling rate may be found to be lower than 5 to 10 concentrates per man per day.

Laboratory Time

The time spent in processing a heavy-mineral concentrate in the laboratory is equal to, or more often than not, far greater than the time needed to take the sample in the field. In the well-equipped laboratory of the Service Geologique du Madagascar the annual output of 13,000 concentrates processed by a staff of 12 (Besairie, 1955, p. 1-3) indicates a rate of 2 hours per sample, which is about the same as that spent by the U. S. Geological Survey on concentrates from the Southeast. More time per sample would not be unusual. Standard textbooks discuss laboratory procedures to be followed in the study of heavy minerals. The rapid method for routine study of many similar concentrates evolved by Jerome Stone, Robert Berman, and associates in the U. S. Geological Survey has been outlined by Berman (1953, p. 120-123) and by Overstreet and others (1956, p. 692-694). Even this method, which bypasses heavy liquids, uses the polarizing microscope only for mineral identification, and resorts to the binocular microscope for grain counts, is very tedious where thousands of samples must be examined.

The method of A. Rittman and E. E. El Hinnawy (1958, p. 67-69) by which the heavy minerals are mounted in molten sulfur (index of refraction 1.93) on glass slides and examined on a heating stage of a petrographic microscope seems to be quite excellent. Advantage is taken of the high index of the molten sulfur to distinguish among the transparent minerals by degree of positive or negative relief, dispersion, and total reflection. Grain counts can be taken more swiftly of concentrates mounted in sulfur than of those mounted in Canada balsam, and the mineral composition of the sulfur-mounted concentrate seemingly is determined with greater precision than is the composition of the concentrate in balsam.

It is not the purpose of this note to describe available optical procedures, but it must be pointed out that none is ideal, or even acceptable, for the rapid identification of minerals in the multitude of concentrates that must be examined where reconnaissance covers large areas.

A. P. Sigov rightly states (Sigov, 1939, p. 6):

> "Concentrates from reconnaissance surveys should be submitted for complete mineral analysis. If an important mineral is overlooked in the first survey, it may require a resurvey of the area, which is a needless waste. Even so, some valuable minerals may be overlooked, either because they are lost in washing, are present in too small quantities, or are difficult to identify."

This emphasizes the value of storing well-labelled and indexed concentrates, as discussed by Junner (1955, p. 345-346), in order that the original concentrates can be reexamined if necessary.

To make heavy-mineral prospecting a thoroughly satisfactory reconnaissance technique the laboratory procedures must be developed so that the most mineralogical data can be recovered by routine methods. Particular attention has to be paid to the rare and sparsely appearing minerals like diamond, gold, and platinum, all of which have been found in the Carolinas, and to the nondescript brown to black semi-opaque to opaque exotic minerals, which are easily overlooked. Research toward development of widely applicable and rapid methods for the mineralogical analysis of concentrates would be a fruitful field for study. Apparently some acceptable routine procedures have been evolved by the Service Geologique du Madagascar (Besairie, 1955, p. 1-3), but the details have not yet been published.

Meanwhile, fresh approaches to laboratory methods are being examined by some members of the Geological Survey who are currently connected with heavy-mineral work. Henry Bell III has developed a system whereby a split of a concentrate is mounted in plastic in a lucite block. After the plastic is cured, the lucite block is sawed in half in a vertical plane through the concentrate. One half of the block is processed as a thin section and the other half as a polished section. Optical procedures and microchemical tests can then be applied to the sections and, after identification, the grains can be counted with a point counter. The polished section can be studied by normal microscopic methods in reflected light. It can be mounted in an X-ray machine and examined by X-ray fluorescence for heavy metals.

X-ray techniques might possibly be developed to give the composition of simple mixtures of minerals such as fractions of different magnetic susceptibility which have been split from one concentrate. A research program involving several years of work would be needed to develop the technique.

Presentation of Data

Data from the heavy-mineral reconnaissance are conveniently summarized on maps. The nature of the data and the purposes of the reconnaissance control the kinds of maps that are made.

Several system of presentation have been used in the Carolinas thus far. They show the minerals present, their relative abundance (percentage) in bedrock, or their relative abundance (percentage) in concentrates from alluvium. In a system used on the Concord and Concord SE quadrangles (Bell and Overstreet, 1960; Overstreet and Bell, 1960), the presence of gold and (or) scheelite in individual drainage basins is shown. In another system the percentage of monazite in the rocks underlying the Shelby quadrangle, N. C. (Yates, R. G., Griffitts,

W. R., and Overstreet, W. C., unpublished data), was shown with logarithmic contours drawn at seven intervals from 0.00001 percent or less to 0.01000 percent or more. In a third system the weight percentages of 15 minerals composing concentrates made from alluvial gravel in the western Piedmont of the Carolinas were contoured at appropriate intervals (Overstreet, and others, 1956, p. 694). Separate maps were made for the common minerals ilmenite, magnetite, garnet, and zircon. Maps combining one common mineral with one less common mineral were made for monazite plus xenotime, rutile plus tourmaline, sillimanite plus kyanite, and epidote plus staurolite. On one map hornblende was shown with two less common minerals, spinel and sphene.

As yet the absolute abundance (weights) of minerals in bedrock or in concentrates has not been presented on maps. However, the total weight of the concentrate has already been shown to vary with the gross lithology of the distributive province. Therefore, in some studies the absolute abundance (weight) of a mineral may be of more use for interpretations than the relative abundance (percentage), and weight would be shown on maps.

APPLICATION IN THE SOUTHEASTERN STATES

Early Work

Examination of the heavy minerals in stream sediments, soils, and saprolite in the Southeastern Piedmont began long ago with the gold prospecting of the 1790's to the 1840's. Following this interest in gold came a period when detrital deposits were also explored for monazite, zircon, sperrylite, platinum, garnet, cassiterite, and diamond. The discoveries made were reported by C. U. Shepard (1852, p. 109), F. A. Genty and W. C. Kerr (1881, p. 72-73), J. W. Mallet (1882, p. 205), A. O. Derby (1891a, p. 206), F. A. Genth (1891, p. 1-85), H. B. C. Nitze (1895, p. 181), C. A. Mezger (1895, p. 822-823), W. E. Hidden and J. H. Pratt (1898a, p. 294; 1898b, p. 463), W.E. Hidden (1898, p. 381), L. C. Graton (1906, p. 116-118), Earle Sloan in 1908 (p. 129-131), and J. H. Pratt and D. B. Sterrett (1909, p. 7). None of these reports are accounts of systematic heavy-mineral reconnaissance, but they do describe many mineral localities shown by placer concentrates. The reports crudely define geochemical provinces in which gold, platinum, monazite, and diamonds occur in the Piedmont.

Current Studies

Current heavy-mineral reconnaissance in the Southeastern States dates from work begun in 1935 by the U. S. Geological Survey. It has been mainly a study of techniques. The techniques for the most part are directed toward the defining of geochemical provinces, establishing backgrounds of the abundances of metals and minerals in the region, and relating these data to the regional geology. Behind this work are several attractive ideas. One thought is that if the abundance of certain metals and minerals is known in a reconnaissance fashion, that is, one sample in 1 to 4 square miles, for regions measuring thousands of square miles, then areas favorable for more detailed study can be pointed out. Anomalies for different metals and industrial minerals can be expected to emerge in different places; thus, great areas should be examined. Syntheses based on such reconnaissance might also attract private interests to survey some localities in detail.

Another thought is that specific structures shown on geologic maps might warrant heavy-mineral study. This idea is being followed in current projects by Survey parties at Concord and Lexington, N. C., where geochemical and geophysical exploration accompanies geologic mapping. It is expected that the methods developed in these areas can be widely applied in the Piedmont and in other regions underlain by thoroughly weathered crystalline rocks.

Two methods of heavy-mineral reconnaissance have evolved. In one method the heavy accessory minerals were collected from weathered rocks. In the other method heavy detrital minerals were collected from stream gravel. Both methods have been modified by the addition of geochemical tests.

Heavy Accessory Minerals from Rocks

Heavy minerals were panned from saprolite by L. M. Prindle and W. A. White and used to help identify the source rocks. The study was on too small a scale to be definitive, but the results were incorporated in a report on the gold deposits of the Piedmont by J. T. Pardee and C. F. Park, Jr. (1948, p. 25-26). Later, J. B. Mertie, Jr., commenced his monumental research into the accessory minerals from more than 500 samples of granitic rocks in the Southeastern States. By 1961 several accounts of this work had been given (Mertie, 1953, p. 1-31; 1954, p. 639-651; 1957, p. 1766-1767). From 1948 to 1951 R. G. Yates, W. R. Griffitts, and the writer panned heavy minerals from 1,200 samples of saprolite in the area of the Shelby quadrangle, N. C. (unpublished data). Interest generated by Mertie's work on heavy minerals in saprolite led to the adoption, with modifications, of his methods by persons outside the Survey. Herbert Yoho (1952, p. 239-244) and V. J. Hurst (1951, p. 244-264) tried the system locally in Georgia in 1951.

Results

The principal results thus far achieved by studies of heavy accessory minerals from rocks in the Southeastern Piedmont are the delineation of belts of monazite-bearing crystalline rocks and the distribution of monazite in crystalline rocks.

The three belts of monazite-bearing crystalline rocks defined by J. B. Mertie, Jr. (1953, pl. 1; 1954, p. 639-651; 1957, p. 1766-1767), extend for hundreds of miles and underlie thousands of square miles in Virginia, North and South Carolina, Georgia, and Alabama. They are geologic and geochemical features of major stature. No comprehensive pictures of the sedimentary, metamorphic, and tectonic development of the Southeastern States will be able to ignore these belts.

The heavy minerals panned from the saprolite in the Shelby quadrangle were examined under the binocular microscope, and the abundance of the monazite in the concentrate was estimated and calculated as a percentage of the rock. The range was from 0.00001 to 0.3 percent. To present these abundances graphically a logarithmic contour interval was used and a map prepared showing monazite in bedrock at concentrations of:

0.00001 percent, and below
0.00003 "
0.00010 "
0.00032 "
0.00100 "
0.00316 "
0.01000 " , and above

The resulting map disclosed that sillimanite schist and gneissic quartz monzonite were preferred hosts for monazite. The contours drawn on abundance of monazite fitted in a general way to the broadest geologic features in the bedrock, and also crudely matched an isorad map prepared from an airborne geophysical survey of the northern half of the quadrangle. The principal difference between the isorad map and the contours based on monazite in bedrock was that thick sequences of residual soil on major interfluves tended to be radiometric highs, owing to residual concentration of monazite, although they were not necessarily above monazite-rich bedrock.

Monazite was so infrequently observed in thin section or in hand

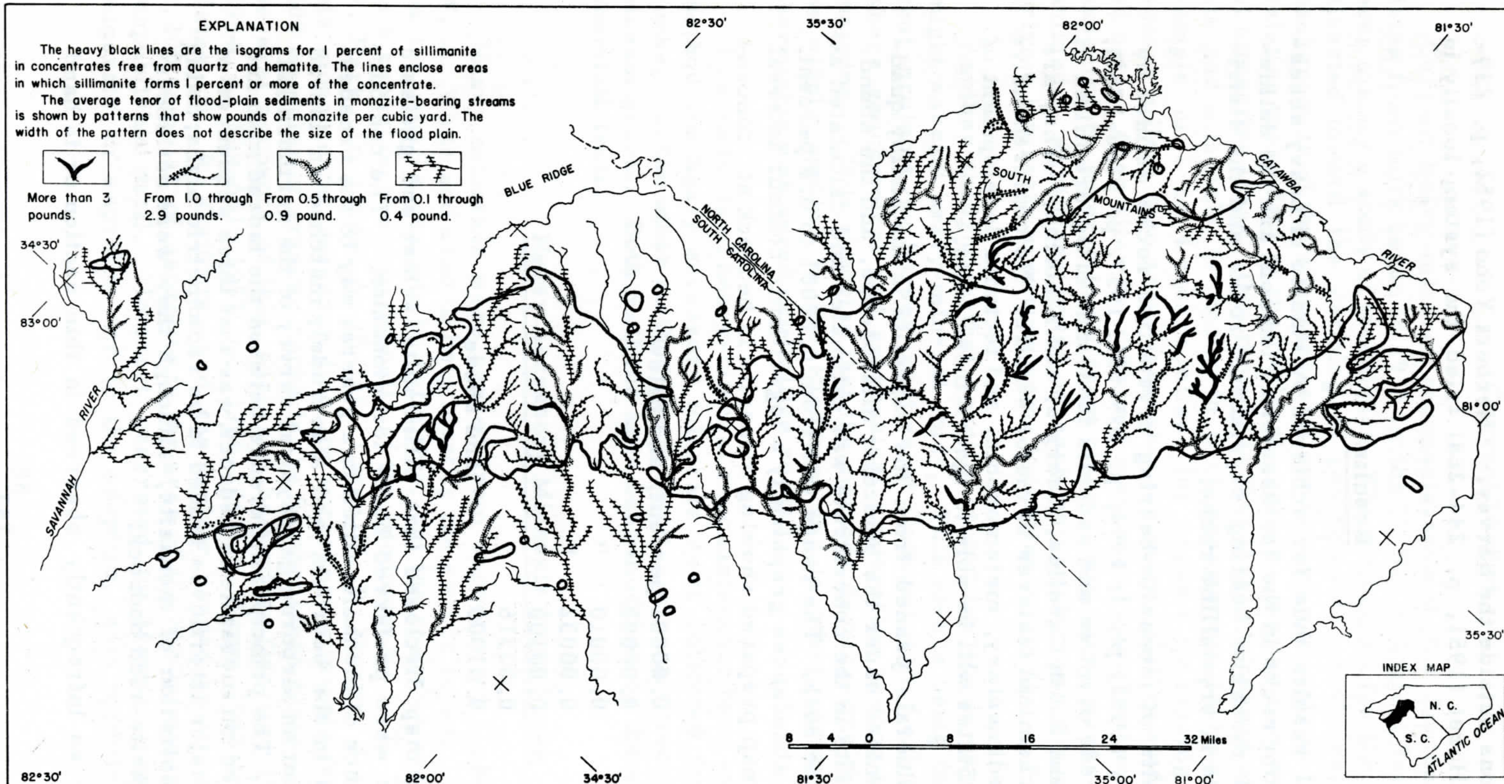

Figure 1. Map showing the location of monazite-bearing streams and the position of the 1-percent isogram for sillimanite between the Savannah and Catawba Rivers, South Carolina and North Carolina.

specimens of rocks from the Shelby area that no approximation of its abundance in the rocks could have been made by usual petrographic methods. Heavy-mineral concentrates prepared from bulk samples of the rock, however, were ideal for a study of the distribution of monazite in the rocks. The technique is an excellent complement to normal petrographic methods.

Heavy Detrital Minerals from Alluvium

The alluvial monazite placers in the western Piedmont of the Carolinas and Georgia were explored between 1951 and 1954 by the U. S. Geological Survey. During this work about, 4,200 concentrates of heavy detrital minerals were collected from alluvial sediments by P. K. Theobald, Jr., A. M. White, J. W. Whitlow, N. P. Cuppels, D. W. Caldwell, and the writer. The minerals were identified by Jerome Stone, Robert Berman, and assistants in the laboratories of the Geological Survey. Geological interpretations of the data were made by the writer and his associates and several preliminary reports have been issued (Overstreet and Griffitts, 1955, p. 549-577; Overstreet, Theobald, Whitlow, and Stone, 1956, p. 692-694; Overstreet, Theobald, and Whitlow, 1959, p. 709-714).

Results

The principal results of the study of heavy detrital minerals from alluvium have been the delineation of regional metamorphic zones, interpretation of the geologic cycle of monazite, and the development of field and laboratory techniques applicable to mineral exploration in areas of weathered rocks.

The mineral composition of concentrates from the alluvial monazite placers was plotted on maps, and weight percentages of the minerals were contoured at the intervals shown in Table 2. Several of the heavy detrital minerals shown on the maps are critical indices to metamorphic grade of rocks in the drainage basins from which the concentrates came. The most useful of the metamorphic index minerals proved to be sillimanite and garnet.

Monazite was found to occur in zones of regional metamorphic climax. Monazite is most abundant in migmatites where the rocks have been metamorphosed to the sillimanite-almandine subfacies of the amphibolite facies. These relations are shown in Figure 1. Figure 1 shows that the richest alluvial deposits of monazite in the western Piedmont of the Carolinas (Overstreet, Theobald, and Whitlow, 1959, p. 710-711) occur in areas enclosed by the 1-percent isogram for sillimanite. This isogram approximately defines the transition between

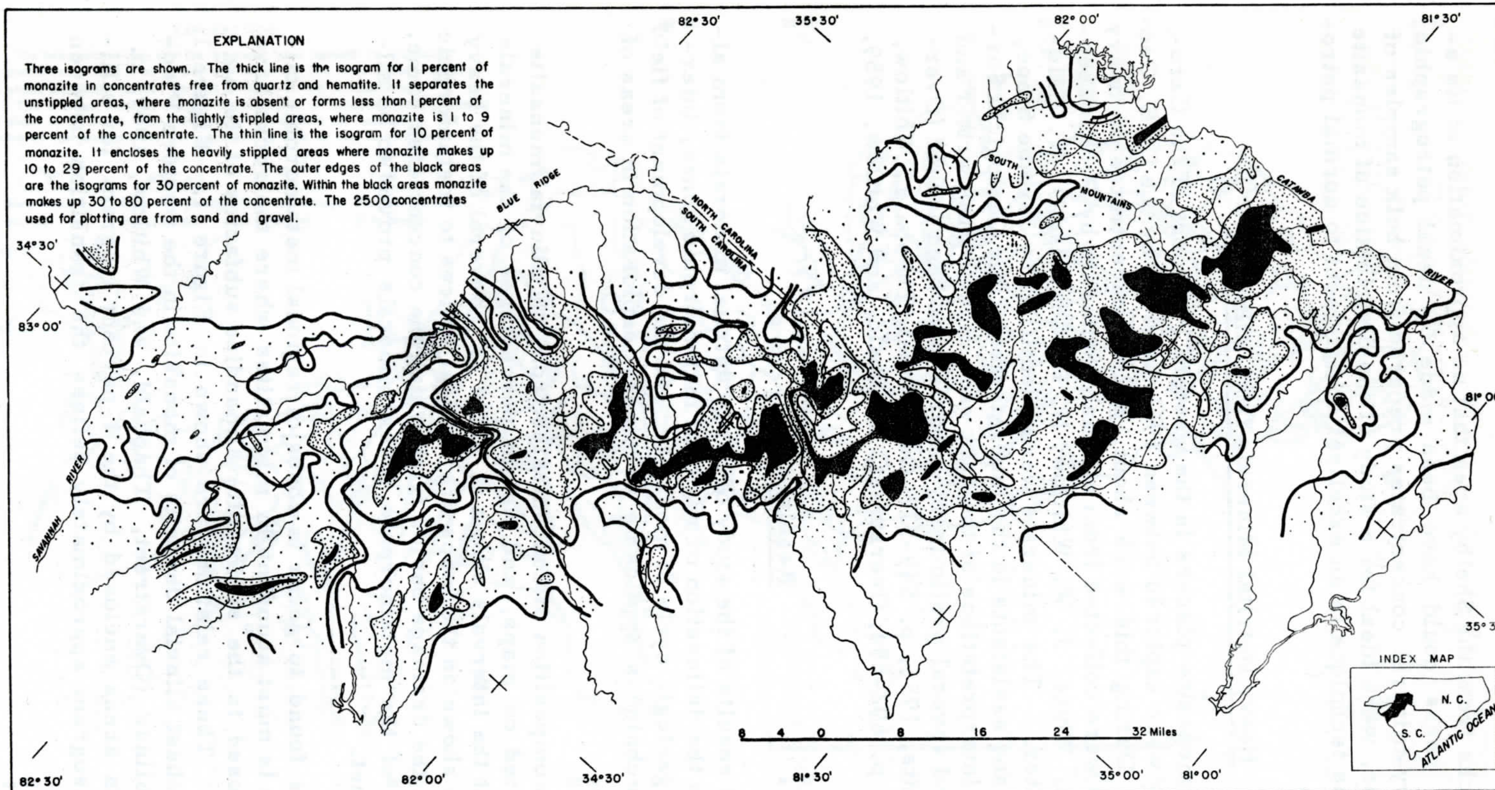

Figure 2 Map showing isograms for monazite between the Savannah and Catawba Rivers, South Carolina and North Carolina.

Table 2. Contour intervals used to outline the distribution of heavy minerals in the western Carolina Piedmont. (Weight percent.)

	Initial contour	Contour interval	Maximum contour
Ilmenite	10	10	90
Magnetite	1	10a	90
Rutile	1	5	20
Garnet	1	10b	70
Zircon	1	10c	50
Monazite	1	10a	80
Xenotime	1	10a	20
Tourmaline	1	5	30
Spinel	1	1	6
Sphene	1	1	3
Staurolite	1	5	90
Kyanite	1	5	25
Sillimanite	1	5	35
Epidote	1	5	80
Hornblende	1	5	50

a. Supplementary contour at 5 percent.
b. Supplementary contours at 5 and 15 percent.
c. Supplementary contours at 2 and 5 percent.

rocks of the kyanite-staurolite subfacies of the amphibolite facies, which occur to the southeast and northwest of the isogram, and higher grade rocks of the sillimanite-almandine subfacies of the amphibolite facies, which occur inside the 1-percent sillimanite isogram (Overstreet and Griffitts, 1955, p. 558-561). In Figure 2 the 1-percent, 10-percent, and 30-percent isograms for monazite are shown. The remarkably close coincidence between the 10-percent isogram for monazite and the 1-percent isogram for sillimanite establishes the regionally concordant trend of these two minerals in this area. It was also found that monazite from sources inside the area bounded by the 1-percent sillimanite isogram was richer in ThO_2 than monazite from sources outside the isogram.

These relations prompted a search of the literature on monazite which revealed that monazite follows a geologic cycle. The chief features of the cycle are a lack of stability of detrital monazite in pelitic sediments during early stages of regional metamorphism, an increase in abundance of metamorphic monazite with rise in metamorphic grade, and an increase in amoung of ThO_2 in monazite with rise in metamorphic grade of the host (Overstreet, 1960, p. B-55-B57).

Trace elements in the heavy-mineral concentrates from the streams were measured by semi-quantitative spectrographic analyses on about one concentrate in 30. Ordinarily the concentrates selected for spectrographic analysis came from the mouths of streams 10 to 20 miles long with drainage basins about 50 square miles in area. Special attention was given for valuable metals such as tin, tungsten, niobium, and tantalum but no unusual concentrations were found. Had any of the analyses disclosed anomalous amounts of the metals, the source of the enrichment could have been traced upstream in the manner used for tungsten in Colorado by P. K. Theobald, Jr., and C. E. Thompson (1959, p. 1-13). Tin was found to be present in quantities from 0.00X to O.X percent in concentrates containing 0.000X to 0.00X percent of beryllium and 0.000X percent of silver. These concentrates came from drainage basins underlain by schist and gneiss intruded by cross-cutting bodies of pegmatite and quartz monzonite. Most of the concentrates with this association of tin, beryllium, and silver came from Cherokee County, S. C., and Cleveland, Gaston, Lincoln, and Catawba Counties, N. C., adjacent to and principally on the west side of the tin-spodumene belt (Kesler, 1944, fig. 1). Concentrates with similar abundances of tin, beryllium, and silver were obtained from the drainage basin of Lawson Fork Creek upstream from the city of Spartanburg, S. C., and from streams in the northwestern corner of Laurens County, S. C.

The techniques of mineral exploration developed during the study of detrital heavy minerals in the western Piedmont have been introduced elsewhere in North Carolina with results that are described in the sections on Metals in alluvium and Trace elements in detrital magnetite.

OTHER GEOCHEMICAL RECONNAISSANCE IN THE SOUTHEAST

Analyses of Water

Analyses of water from wells in the Southeastern states have long been made in the studies of quality of water carried on in cooperative arrangements between the States and the U. S. Geological Survey. These analyses are, historically, the second form of geochemical prospecting introduced into the region. Although the original and chief purpose of the analyses was not geochemical prospecting, it is now evident that the results of the analyses define certain geochemical provinces. In a recent paper H. E. LeGrand discusses the chemical character of water in the crystalline rocks of North Carolina and the geochemical provinces it defines. He observes (LeGrand, 1958, p. 178):

> "In geochemical exploration for mineral deposits, attention is commonly devoted chiefly to the chemical behavior of a specific mineral or suite of minerals. The rapid development of geochemical exploration in recent years justifies a broadening in the scope of studies so that geochemical norms and anomalies in specific rock terranes can be determined; as this is done a base can be formed from which further geochemical studies can aid either directly or indirectly in mineral exploration. A case in point is the evaluation of the chemical character of water in igneous and metamorphic rocks. . .
>
> ". . . In their chemical character and that of the water derived from them, the rocks of North Carolina can be divided into two groups. The first includes granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs; these rocks resemble granite in composition. The second group includes diorite, gabbro, hornblende gneiss, and andesite flows and tuffs; these rocks resemble diorite in composition. The granite group yields a soft, slightly acidic water that is low in dissolved mineral constituents; the diorite group yields a hard, slightly alkaline water that is relatively high in dissolved material.
>
> "Lithologic determinations based on the chemical character of ground water are generally reliable in regions of similar climate and topography. Anomalies in dissolved mineral constituents that are not due to differences in rock type, climate, or topography may indicate either abnormal structural conditions, resulting in abnormal rates of circulation of the water, or the presence of concentrated mineral deposits."

Much background data will come from the projects on the quality of water. If the analyses were extended to include the abundances of some other elements in the water, the regional geochemical usefulness of the analyses would be increased, and an understanding of geochemical norms, as cited by LeGrand, would be improved.

Metals in Alluvium

Methods

Determining and plotting the abundances of metals in alluvium in a systematic regional reconnaissance is historically the third system of geochemical prospecting used in the Piedmont. It was begun in the Carolinas by A. A. Stromquist at Lexington in 1955 and by Henry Bell, III, and the writer at Concord in 1956. This regional reconnaissance has been continued to this writing by A. A. Stromquist, A. M. White, and Henry Bell, III.

Samples consisted of 100 grams of slightly carbonaceous, silty to clayey sediment. This class of sediment was used because it is common in the streams and is likely to have absorbed metallic ions from the water. The samples were dug from the present channels of streams whose drainage basins upstream from the sample are 0.5 to 2.0 square miles in area. A total of 145 samples was taken in an area of 118 square miles.

The amounts of lead, zinc, and molybdenum were determined by the rapid analytical methods described by Lakin, Almond, and Ward (1952, p. 14-21). Copper was determined by procedures described by Almond (1955, p. 6). An attempt was made to measure the tungsten in the samples using an analysis discussed by Lakin and others (1952, p. 24) because many heavy-mineral concentrates from the area contain scheelite, but the amount of tungsten in the sediment was too small to detect chemically.

Results

The results of the analyses were plotted on 7 1/2-minute quadrangle base maps (Bell and Overstreet, 1960; Overstreet and Bell, 1960), and the drainage basins that showed comparatively high values for the metals were outlined on the maps. Background values for copper, lead, zinc, and molybdenum in alluvium from streams in the Concord area, N. C., are 20 to 80 ppm for each metal. Alluvium that contained metals in moderately greater abundance than background seems to have come from basins which drain areas containing specific geologic features such as a long shear zone or the contact between granite and gneiss.

The distribution of gold and scheelite in the heavy-mineral concentrates was also shown on the maps. Scheelite was found to occur as far as 10 miles west of previously reported limits. The alluvium in certain drainage basins contained above-background amounts of several metals and either or both gold and scheelite. These basins tended to follow major fault zones or the margins of granite plutons.

It is unlikely that the association of above-background amounts of the base metals with gold and (or) scheelite in these areas is necessarily related to commercial ore bodies, but these areas, when regionally known and compared, will provide a useful base for more refined geological exploration for ore deposits.

Trace Elements in Detrital Magnetite

The abundance of trace elements in magnetite have been under investigation by P. K. Theobald, Jr., and others since 1958 (Theobald and Thompson, 1959, p. 1-13; Theobald and Havens, 1960, p. 223). They have found a wide range in the abundance of copper, lead, zinc, tin, titanium, manganese, molybdenum, antimony, silver, and beryllium in magnetite from difference geologic environments. Analyses of magnetite separated from concentrates panned from the saprolites of eight kinds of crystalline rocks exposed at the Isenhour quarry in Cabarrus County, N. C., (Bell and Overstreet, 1959, p. 1-5) showed that magnetite from syenite was rich in zinc compared to magnetite from granite and granodiorite exposed at the quarry.

Analyses of detrital magnetite separated from placer concentrates from the western Piedmont of the Carolinas show a relation between the regional abundance of certain trace elements and the amount of magnetite in the concentrate. Lead, copper, tin, titanium, antimony, and beryllium increase as the amount of magnetite decreases in the concentrate. Manganese and zinc increase in abundance as the amount of magnetite increases in the concentrate. The abundance of molybdenum and silver seems to be unrelated to the amount of magnetite in the concentrate. The amount of magnetite in the concentrate is related to the original composition and degree of metamorphism of the rocks in the distribute province from which the concentrate came; pelitic sediments at the highest metamorphic grade contain the least magnetite. The trends of the abundance of the trace elements in the magnetite can be related to broad regional geologic features. The rare samples of magnetite with anomalously large amounts of one or more trace elements appear to be related to some local change in lithology.

The analyses of trace elements in detrital magnetite may prove to be the best adjunct to heavy -mineral reconnaissance thus far introduced into the southeastern Piedmont.

CONCLUSIONS

The utility of heavy-mineral reconnaissance has been tested in Brazil, Nigeria, Ceylon, the Gold Coast, Madagascar, Sierra Leone, Malaya, Borneo, India, Russia, Pakistan, and the United States. At various times since 1889 geologists interested in regional exploration for ore deposits have advocated its use. Applications of heavy-mineral reconnaissance on a regional scale in the Southeastern Piedmont have contributed to the knowledge of regional metamorphism, of the distribution of monazite, sillimanite, gold, and scheelite, of the variation in trace amounts of Cu, Pb, Zn, Ti, Mn, Be, Sn, and Mo in magnetite, and of field and laboratory procedures. Useful negative information has also been obtained. For instance, it has been shown that the western Piedmont between the Savannah and Catawba Rivers is relatively unfavorable as a place to search for gold, and for the ores of tungsten chromium, niobium, and tantalum. Areas for research in field and laboratory procedures, particularly the latter, are recognized. The most evident result of past work is to show that the acceptance of heavy-mineral reconnaissance as a rapid method of geochemical exploration hinges almost entirely on the development of swift and accurate new ways to identify the minerals in a concentrate.

REFERENCES

Almond, Hy, 1955, Rapid field and laboratory methods for the determination of copper in soils and rocks: U. S. Geol. Survey Bull. 1036-A, p. 1-18.

Andel, T. H., van, 1950, Provenance, transport and deposition of Rhine sediments: Wageningen, H. Veenman and Sons, P. 1-129.

Bates, R. G., and Wedow, Helmuth, Jr., 1953, Preliminary summary review of thorium-bearing mineral occurrences in Alaska: U. S. Geol. Survey Circ. 202, p. 1-13.

Bell, Henry, III, and Overstreet, W. C., 1959, Relations among some dikes in Cabarrus County, North Carolina: South Carolina Div. Geol., Geol. Notes, v. 3, no. 2, p. 1-5.

Bell, Henry, III, and Overstreet, W. C., 1960, Geochemical and heavy-mineral reconnaissance of the Concord quadrangle, Cabarrus County, North Carolina: U. S. Geol. Survey M. F-234.

Berman, Robert, 1953, A nomogram for obtaining per cent composition by weight from mineral-grain counts: Jour. Sed. Petrology, v. 23, no. 2, p. 120-123.

Besairie, Henri, 1953, Carte minière et des indices de Madagascar: notices explicatives; Madagascar Service Géol., Travaux no. 52, p. 1-154, 1955, Rapport annuel du Service Géologique pour l'annee 1955: Madagascar Dir. Mines et de la Géol., Rapport Ann. Ser. Géol. 1955, p. 1-188.

Boswell, P. G. H., 1933, On the mineralogy of sedimentary rocks; a series of essays and a bibliography: London, Thomas Murby and Co., p. 1-393.

Brammall, Alfred, 1928, Dartmoor detritals; a study in provenance: Geologists' Assoc. Proc., v. 39, p. 28-48.

Dana, E. S., 1932, A textbook of mineralogy with an extended treatise on crystallography and physical mineralogy; 4th ed., rev. and enl. by W. E. Ford: New York, John Wiley and Sons, Inc., p. 1-851.

Danilchik, Walter, and Tahirkheli, R. A. Khan, 1959, An investigation of alluvial sands for uranium and minerals of economic importance; the Indus, Gilgit, Nagar and Hunza Rivers, Gilgit Agency, West Pakistan: Pakistan Geol. Survey Inf. Release 11, p. 1-7.

Day, D. T., 1905, Second preliminary report on investigation of black sands, in Black sands of the Pacific slope, exhibit C: U. S. Cong., Senate, 59th Cong., 1st Sess., Doc. 65, p. 15-24.

__________1907, Black sands of the Pacific Coast: Franklin Inst. Jour., v. 164, p. 141-153.

Day, D. T., and Richards, R. H., 1906a, Investigations of black sands from placer mines, in Emmons, S. F., and Eckel, E. C., 1906, Contributions to economic geology 1905; U. S. Geol. Survey Bull. 285, p. 150-164.

__________1906b, Useful minerals in the black sands of the Pacific slope: U. S. Geol. Survey Mineral Resources U. S., 1905, p. 1175-1258.

Derby, O. A., 1889, On the occurrence of monazite as an accessory element in rocks: Am. Jour. Sci., Ser. 3, v. 37, no. 218, p. 109-113.

__________1891a, On the separation and study of the heavy accessories of rocks: Rochester Acad. Sci. Proc., v. 1, brochure 2, p. 198-206.

Derby, O. A., 1891b, On the occurrence of xenotime as an accessory element in rocks: Am. Jour. Sci., ser. 3, v. 41, no. 244, p. 308-311.

__________1897, Monazite and xenotime in European rocks: Mineralog. Mag., v. 11, p. 304-310, London.

__________1898, On the accessory elements of itacolumite, and the secondary enlargement of tourmaline: Am. Jour. Sci., ser. 4, v. 5, no. 27, p. 187-192.

__________1899, On the association of argillaceous rocks with quartz veins in the region of Diamantina, Brazil: Am. Jour. Sci., ser. 4, v. 7, no. 41, p. 343-356.

__________1900a, Notes on certain schists of the gold and diamond regions of eastern Minas Geraes, Brazil: Am. Jour. Sci., ser. 4, v. 10, no. 57, p. 207-216.

__________1900b, Notes on monazite: Am. Jour. Sci., ser. 4, v. 10, no. 57, p. 217-221.

__________1902, On the occurence of monazite in iron ore and graphite: Am. Jour. Sci., ser. 4, v. 13, no. 75, p. 211-212.

__________1905, The Bahia diamond fields: Brazilian Eng. Mining Rev., v. 2, no. 11, p. 163-165.

Dunstan, W. R., 1906, Reports on the mineral survey of Southern Nigeria for 1903-4 and 1904-5: Great Britain Colonial Office, Colonial Repts., Misc., no. 33, Southern Nigeria, p. 3-33.

__________1910, Report on the results of the mineral survey of Ceylon, 1906-7 and 1907-8: Great Britain Colonial Office, Colonial Repts., Misc. no. 74, Ceylon, p. 2-70.

Emberger, A., 1956, Produits utiles de l' Ankaizina, in Besairie, Henri, 1956, Rapport Annuel du Service Géologique pour l'Annee 1956: Madagascar Dir. Mines et de la Géol., Rapport Ann. Ser. Géol. 1956, p. 53-59.

Ewing, C. J. C., 1931, A comparison of the methods of heavy mineral separation: Geol. Mag. [London], v. 68, p. 136-140.

Fitch, F. H., 1952, The geology and mineral resources of the neighbourhood of Kuantan, Pahang: Federation of Malaya Geol. Survey Dept. Mem. 6 (new series), p. 1-144.

Freise, Ferdinand, 1910, Die Monazitvorkommen in Gebiete des oberen Muriahé--und Pombaflusses im Staate Minas Geraes, Brasilien: Preussen Berg-, Hutten-, u. Salinenwesen Zeitschr., v. 58, B, p. 47-64.

Genth, F. A., 1891, The mineral of North Carolina: U. S. Geol. Survey Bull. 74, p. 5-119.

Genth, F. A., and Kerr, W. C., 1881, The minerals and mineral localities of North Carolina, being Chapter I of the second volume of the geology of North Carolina: Raleigh, P. M. Hale and Edwards, Broughton and Co., p. 1-122.

Ginzburg, I. I., 1960, Principles of geochemical prospecting: London, Pergamon Press, p. 1-311.

Graton, L. C., 1906, Reconnaissance of some gold and tin deposits of the southern Appalachians: U. S. Geol. Survey Bull. 293, p. 3-134.

Guigues, Jean, 1955, Le Champ pegmatitique d' Ampandramaika-Malakialina, in Besairie, Henri, Rapport Annuel du Service Géologique pour l'Annee 1955: Madagascar Dir. Mines et de la Géol., Rapport Ann. Ser. Géol. 1955, p. 43-50.

Haile, N. S., 1954, The geology and mineral resources of the Strap and Sadong valleys, West Sarawak, including the Klingkang Range coal: British Territories in Borneo Geol. Survey Dept. Mem. 1, p. 1-150.

Hawkes, H. E., 1957, Principles of geochemical prospecting: U. S. Geol. Survey Bull. 1000-F, p. 225-355.

Hidden, W. E., 1898, Occurrence of sperrylite in North Carolina: Am. Jour. Sci., ser. 4, v. 6, no. 35, p. 381-383.

Hidden, W. E., and Pratt, J. H., 1898a, On rhodolite, a new variety of garnet: Am. Jour. Sci., ser. 4, v. 5, no. 28, p. 294-296.

Hidden, W. E., and Pratt, J. H., 1898b, On the associated minerals of rhodolite: Am. Jour. Sci., ser. 4, v. 6, no. 36, p. 463-468.

Hurst, V. J., 1951, Heavy minerals in saprolite differentiation: Georgia Dept. Mines, Mining and Geology, Geol. Survey Bull 60, p. 244-264 [1953].

Junner, N. R., 1943, The diamond deposits of the Gold Coast with notes on other diamond deposits in West Africa: Gold Coast Geol. Survey Bull. 12, p. 2-52.

__________ 1955, Discussion. The gold pan--a neglected geological tool: Econ. Geology, v. 50, no. 3, p. 345-346.

Kesler, T. L., 1944, Correlation of some metamorphic rocks in the central Carolina Piedmont: Geol. Soc. America Bull., v. 55, no. 6, p. 755-782.

Killeen, P. L., and Ordway, R. J., 1955, Radioactivity investigations at Ear Mountain Seward Peninsula, Alaska, 1945: U. S. Geol. Survey Bull. 1024-C, p. 59-94.

Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of sedimentary petrography: New York, Appleton-Century-Crofts, Inc., p. 3-549.

Lakin, H. W., Almond, Hy, and Ward, F. N., 1952, Compilation of field methods used in geochemical prospecting by the U. S. Geol. Survey: U. S. Geol. Survey Circ. 161, p. 1-34.

LeGrand, H. E., 1958, Chemical character of water in the igneous and metamorphic rocks of North Carolina: Econ. Geology, v. 53, no. 2, p. 178-189.

Mallet, J. W., 1882, Notes on work by students of practical chemistry in the laboratory of the University of Virginia. No. XI: Chem. News, v. 46, no. 1197, p. 204-206, London.

Memminger, Lucien, 1917, Unfavorable report on Mysore monazite: U. S. Bur. Foreign and Domestic Commerce, Commerce Repts., v. 271, p. 681.

Mertie, J. B., Jr., 1925, Geology and gold placers of the Chandalar district, Alaska: U. S. Geol. Survey Bull. 773-E, p. 216-263.

__________ 1953, Monazite deposits of the southeastern Atlantic states: U. S. Geol. Survey Circ. 237, p. 1-31.

__________ 1954, The gold pan: a neglected geological tool: Econ. Geology, v. 49, no. 6, p. 639-651.

Mertie, J. B., Jr., 1957, Geologic occurrence of monazite and xenotime in the Southeastern states [abs.] : Geol. Soc. America Bull., v. 68, no. 12, pt. 2, p. 1766-1767.

Mezger, C. A., 1895, The monazite districts of North and South Carolina: Am. Inst. Mining Engineers Trans., v. 25, p. 822-826, 1036-1040 [1896].

Nelson, A. E., West, W. S., and Matzko, J. J., 1954, Reconnaissance for radioactive deposits in eastern Alaska, 1952: U. S. Geol. Survey Circ. 348, p. 1-21.

Nitze, H. B. C., 1895, North Carolina monazite: Chem. News, v. 71, no. 1846, p. 181.

Overstreet, W. C., 1960, Metamorphic grade and the abundance of ThO_2 in monazite, in Short papers in the geological sciences: U. S. Geol. Survey Prof. Paper 400-B, p. B55-B57.

Overstreet, W. C., and Bell, Henry, 3d, 1960 Geochemical and heavy-mineral reconnaissance of the Concord SE quadrangle, Cabarrus County, North Carolina: U. S. Geol. Survey MF-235.

Overstreet, W. D., and Griffitts, W. R., 1955, Inner Piedmont belt, in Russell, R. J., ed., 1955, Guides to southeastern geology; Geol. Soc. America, Guidebook 1955 ann. meeting, p. 549-577.

Overstreet, W. C., Theobald, P. K., Jr., and Whitlow, J. W., 1959, Thorium and uranium resources in monazite placers of the western Piedmont, North and South Carolina: Mining Eng., v. 11, no. 7, p. 709-714.

Overstreet, W. C., Theobald, P. K., Jr., Whitlow, J. W., and Stone, Jerome, 1956, Heavy mineral prospecting, in International Conf. Peaceful Uses Atomic Energy, Geneva 1955, Proc., v. 6, p. 602-694.

Pardee, J. T., and Park, C. F., Jr., 1948, Gold deposits of the southern Piedmont: U. S. Geol. Survey Prof. Paper 213, p. 1-156.

Peele, Robert, and Church, J. A., 1941, Mining engineers' handbook, 3rd ed.: New York, John Wiley and Sons, Inc., p. 1-01 to 14-66, plus 63.

Pratt, J. H., and Sterrett, D. B., 1909, Monazite industry in the Carolinas: Mining Jour. [London], v. 86, no. 3854, p. 7.

Richardson, J. A., 1939, The geology and mineral resources of the neighborhood of Raub, Pahang, Federated Malay States, with an account of the geology of the Raub Australian gold mine: Federated Malay States Geol. Survey Dept., p. 1-166.

Rittmann, A., and El Hinnawy, E. E., 1958, A note on the quantitative mineralogical analysis of black sands: Egyptian Jour. Geol., v. 2, no. 1, p. 67-69.

Robinson, G. D., Wedow, Helmuth, Jr., and Lyons, J. B., 1955, Radioactivity investigations in the Cache Creek area, Yenta district, Alaska, 1945: U. S. Geol. Survey Bull., 1024-A, p. 1-23.

Scrivenor, J. B., 1911, Federated Malay States Geologist's annual report for the year 1910: Federated Malay States Government Gazette, Supplement, p. 1-3, Kuala Lumpur.

Shepard, C. U., 1852, A treatise on mineralogy: New Haven, B. L. Hamlen, 3rd ed., p. 1-451.

Sigov, A. P., 1939, Prospecting by heavy mineral studies [abs. by H. E. Hawkes from Ural Sci. Research Inst. Geol., Prospecting and Econ. Mineral. and Sverdlovsk Mining Inst. Trans., no. 4, 64 p.] : U. S. Geol. Survey open-file rept., p. 1-17.

Sloan, Earle, 1908, Catalogue of the mineral localities of South Carolina: South Carolina State Devel. Board, Div. Geol., reprint, p. 7-505 [1958] .

Smithson, Frank, 1930, The reliability of frequency-estimations of heavy-mineral suites: Geol. Mag. [London] , p. 67, p. 134-136.

Taggart, A. F., 1945, Handbook of mineral dressing, ores and industrial minerals: New York, John Wiley and Sons, Inc., p. 1-01 to 22-76 plus 47.

Theobald, P. K., Jr., 1957, The gold pan as a quantitative geologic tool: U. S. Geol. Survey Bull. 1071-A, p. 1-54.

Theobald, P. K., Jr., and Havens, R. G., 1960 Base metals in biotite, magnetite, and their alteration products in a hydrothermally altered quartz monzonite porphyry sill, Summit County, Colorado [abs.] : Geol. Soc. America, Program, 1960 ann. meeting, p. 223.

Theobald, P. K., Jr., and Thompson, C. E., 1959, Geochemical prospecting with heavy-mineral concentrates used to locate a tungsten deposit: U. S. Geol. Survey Circ. 411, p. 1-13.

Thomson, Thomas, 1810, Chemical analysis of a black sand, from the River Dee, in Aberdeenshire: Philos. Mag., v. 1, p. 98-105, London.

Waters, A. E., Jr., 1934, Placer concentrates of the Rampart and Hot Springs districts: U. S. Geol. Survey Bull. 844-D, p. 227-246.

Wedow, Helmuth, Jr., 1954, Reconnaissance for radioactive deposits in the Eagle-Nation area, east-central Alaska, 1948: U. S. Geol. Survey Circ. 316, p. 1-9.

West, W. S., 1953, Reconnaissance for radioactive deposits in the Darby Mountains, Seward Peninsula, Alaska, 1948: U. S. Geol. Survey Circ. 300, p. 1-7.

West, W. S., and Benson, P. D., 1955, Investigations for radioactive deposits in southeastern Alaska: U. S. Geol. Survey Bull. 1024B, p. 25-57.

Wilford, G. E., 1953, Progress report: British Territories in Borneo Geol. Survey Dept. Ann. Rept. for 1952, p. 32-34.

Yoho, Herbert, 1952, Provenance study of the heavy minerals in the streams of the gold belt portions of Lumpkin and White Counties, Georgia: Georgia Dept. Mines, Mining and Geology, Geol. Survey Bull. 60, p. 239-244, [1953] .

Thomson, Thomas, 1818, Chemical analysis of a black sand, from the River Dee, in Aberdeenshire: Philos. Mag., v. 1, p. 96-105, London.

Waters, A. E., Jr., 1958, Placer concentrates of the Rampart and Hot Springs districts: U. S. Geol. Survey Bull. 844-D, p. 227-246.

Wedow, Helmuth, Jr., 1954, Reconnaissance for radioactive deposits in the Eagle-Nation area, east-central Alaska, 1949: U. S. Geol. Survey Circ. 316, p. 1-9.

West, W. S., 1953, Reconnaissance for radioactive deposits in the Darby Mountains, Seward Peninsula, Alaska, 1948: U. S. Geol. Survey Circ. 300, p. 1-7.

West, W. S., and Benson, P. D., 1955, Investigations for radioactive deposits in southeastern Alaska: U. S. Geol. Survey Bull. 1024-B, p. 25-57.

Wilford, G. E., 1953, Progress report: British Territories in Borneo Geol. Survey Dept. Ann. Rept. for 1952, p. 12-26.

Yoho, Herbert, 1952, Preliminary study of the heavy minerals in the streams of the gold belt portions of Lumpkin and White Counties, Georgia: Georgia Dept. Mines, Mining and Geology Geol. Survey Bull. 60, p. 259-264. (1953).

ENVIRONMENTAL STUDIES OF THE CRETACEOUS MOUNT LAUREL AND WENONAH SANDS OF NEW JERSEY

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ABSTRACT

A study of the grain size distribution and heavy mineral of the Mount Laurel and Wenonah sands has indicated that these formations were deposited under a near shore marine environment, except for local variations in the northeastern part of the outcrop, which indicated deeper water. A high percentage of glauconite in several well samples down dip from the outcrop, also indicated deeper water and slightly reducing conditions. A comparison of statistical values was made, and the Mount Laurel tends to be coarser grained than the Wenonah at several localities. The Mount Laurel is a medium sand, and the Wenonah is a fine sand, on the basis of these localities, but there was no consistency in the statistical values of the remaining localities to warrant separation on this basis. The heavy mineral suite of the Mount Laurel and Wenonah sands contains andalusite, chloritoid, epidote, garnet, kyanite, mica, rutile, sillimanite, staurolite, tourmaline, zircon, and hornblende. The same heavy minerals occur in varying proportions along the strike of the outcrop, and do not appear to have been derived from any restricted source. The metamorphic rocks of the Piedmont or New England Prong, and igneous and sedimentary rocks of the Triassic Lowland, or Valley and Ridge Province, as well as the older Cretaceous sediments all could have played a part in supplying heavy minerals to the Mount Laurel and Wenonah Sands.

GENERAL CHARACTER OF THE MOUNT LAUREL AND WENONAH SANDS

The Mount Laurel and Wenonah sands* of New Jersey crop out in a belt striking northeast-southwest from Raritan Bay where it is 2500 feet wide to the Delaware River near Salem, where it is 7500 feet wide. In the northeastern part, near Holmdel, where streams have cut down through the overlying Navesink, two V-shaped inliers are exposed also. Since the dip is low, averaging 35 feet per mile to the southeast, formation boundaries essentially follow the contours. The combined thickness of the two formations varies from 30 to 75 feet.

Lithologically, the two units are difficult to separate, and for this reason have been mapped as a single unit. However, at a few localities the lower part (Wenonah) is a fine micaceous sand, while the upper part (Mount Laurel) is a slightly coarser sand and contains considerable glauconite. On the other hand, the fossils from the two formations are distinct, and for this reason the Monmouth-Matawan boundary has been placed between them. The Wenonah fauna is largely recurrent from the Woodbury and contains a few fossils in common with the Marshalltown. The problematical fossil tube (?) Halymenites major is characteristic of the Wenonah at a number of localities in New Jersey and Delaware. The Mount Laurel is characterized by Belemnitella americana, Choristothyris plicata, Exogyra costata, and E. cancellata. Faunally, the Mount Laurel is almost identical with the overlying Navesink, although quite different lithologically. In Delaware the Mount Laurel-Wenonah boundary is very distinct, but the Navesink and Mount Laurel are difficult to separate and are combined into one unit, the Navesink-Mount Laurel (Groot, Organist, and Richards, 1954)

Well records show that the Mount Laurel and Wenonah sands have a wide areal extent and reach a depth of 2150 feet at Atlantic City (Richards, 1945). This is the maximum depth on record for the formation, and is also the deepest well in the New Jersey Coastal Plain. In a few wells the Mount Laurel and Wenonah sands are very glauconitic.

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*Although the Wenonah has recently been designated a "formation" rather than a "sand" (Owens and Minard, 1960), for convenience the term "sand" will be used in the present paper.

OUTCROP LOCALITIES AND WELL LOCATIONS

A total of 39 outcrop localities, numbers 0 through 38 (Figure 1), from Atlantic Highlands in the north to Auburn in the south, a distance of 85 miles were studied. One locality, number 8, is situated in the inlier in the vicinity of Holmdel. Another, number 7, is located outside of the outcrop, as shown on the state geological map, and indicates extension of the Mount Laurel and Wenonah sands into this area.

Samples from 5 wells, designated as W-1, W-2, W-3, W-4, and W-5 were studied. These were located at Atlantic City, Fort Dix, Lakewood, Neptune Township, and Pine Valley respectively. These were all ditch samples obtained by either cable tool or rotary methods, so the danger of contamination is much greater than in the outcrop samples. The depth to the top of the Mount Laurel and Wenonah sands ranges from 140 feet below sea level at Pine Valley to 2145 feet below sea level at Atlantic City.

MECHANICAL ANALYSIS

The primary purpose of a mechanical analysis of the Mount Laurel and Wenonah sands was to determine the grain-size frequency distribution for interpretation of the environment of deposition. In addition, attempts were made to separate the Mount Laurel from the Wenonah on the basis of their grain-size distribution. An analysis of this type involved the determination of the ranges of sizes of the grains and the relative abundance in each size range. Since the particle sizes of the Mount Laurel and Wenonah are largely limited to sand size, sieving was the method used.

The sieves used were the United States Standard Sieve Series which are based on a ratio of the square root of 2. Their grade limits were 1.4, 1.0, .71, .50, .35, .25, .177, .088, and .062 millimeters.

Quartile measures are used in presenting the data because they can easily be determined from cumulative curves, and three quartile measures will suffice for all statistical computations. These values are the median and the first and third quartiles, all of which can be read directly from the cumulative curve. The median (Md) is the mid-point in the size distribution, the first quartile (Q_1) is that diameter which has 25 per cent of the distribution smaller than itself,

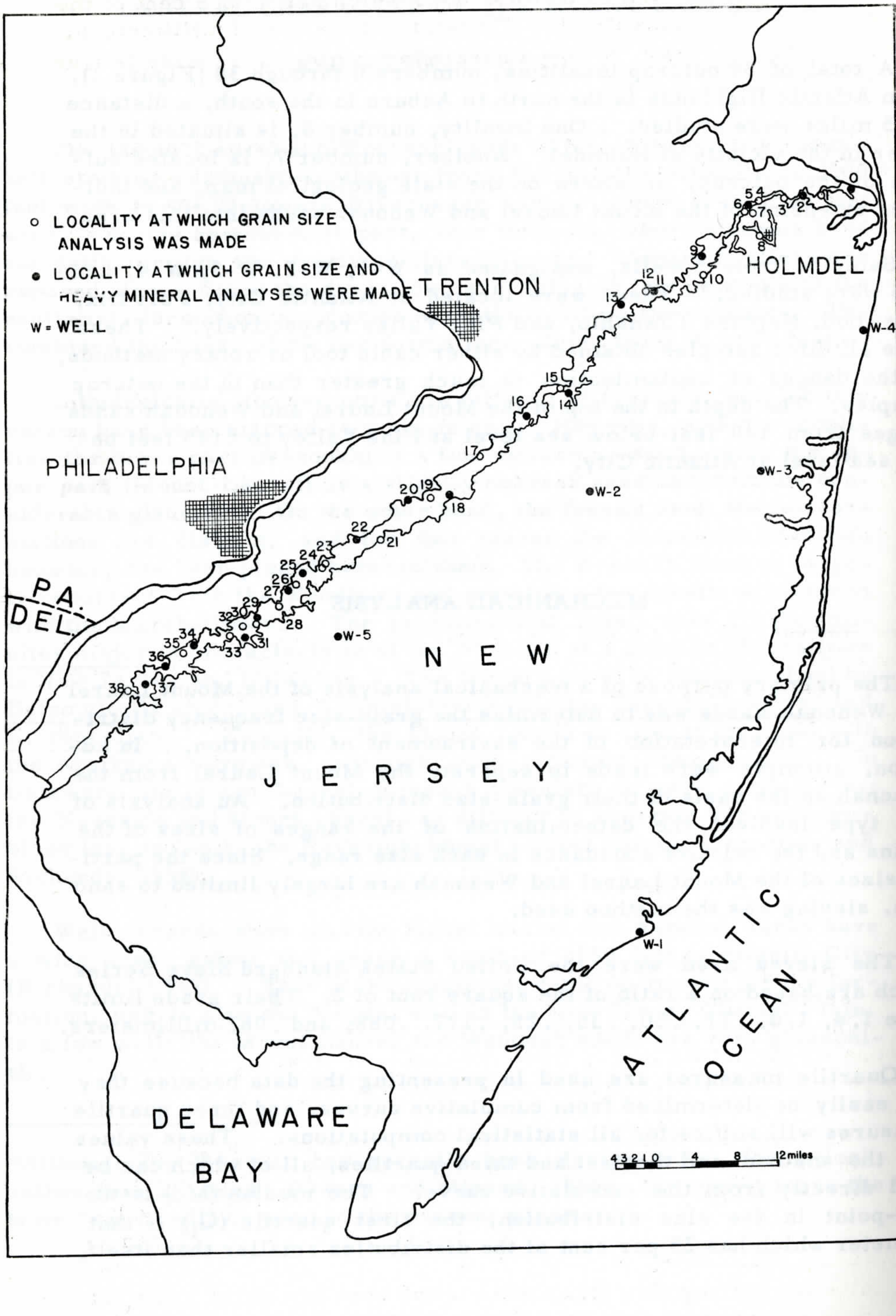

Figure 1. Sample localities

and the third quartile (Q_3) is that diameter which has 75 per cent of the distribution smaller than itself. Therefore, in terms of millimeters, Q_3 has the larger value, and Q_1 the smaller, while the reverse is true when the phi* scale is used.

The sorting coefficient (So) is a measure of the dimensional spread of a sediment. Trask (1932) first introduced this coefficient which expresses the measure of the average spread of size distribution between the first and third quartiles. The formula for determining this coefficient is: $So = \sqrt{Q_3 / Q_1}$ where Q_1 and Q_3 are expressed in millimeters. If the sorting coefficient exceeds 4.5, the sediment is poorly sorted; if it is about 3.0, the sediment has normal sorting, and if it is less than 2.5, the sample is well sorted.

The skewness (Sk) is a measure of the tendency of sediments to spread on one side or the other of the median diameter of the size distribution. As introduced by Trask (1932) skewness is the ratio of the largest quartile and median compared to the ratio of the median and the smaller quartile. This relationship when simplified is:

$$Sk = \frac{Q_1 \; Q_3}{Md_2}$$

where the quartile measures are expressed in millimeters. A perfectly symmetrical distribution has a skewness value of 1. When skewness values are more than 1, the coarse admistures exceed the fine. When the skewness values are less than 1, the fine admixtures exceed the coarse.

HEAVY MINERAL ANALYSIS

The main purpose of separating and identifying the heavy minerals from a series of Mount Laurel and Wenonah samples was to establish, if possible, the existence of a distinctive heavy mineral suite in the outcrops of the formation. Once defined, the heavy mineral suite could be considered in relation to such questions as:

1. What can be learned from the heavy minerals concerning the direction of source, mode of transportation, and environment of deposition?

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*Phi units are the negative logarithms to the base two of the grain diameters in millimeters, and therefore substitutes whole numbers for fractions.

2. What are the similarities and differences between this suite and those of the other sediments of the Atlantic Coastal Plain?

3. Do the heavy minerals change along the strike of the formation?

4. Can the Mount Laurel be separated from the Wenonah on the basis of heavy minerals?

In the present investigation, all the size grades from .50 to .062 were studied, since a study of only one or two size grades might overlook some critical mineral which is concentrated in another size range.

In determining the number of grains to be counted from each sample, the errors of sampling (i.e., distribution in a slide) and counting had to be considered. Dryden (1931) studied this problem, and found that the accuracy increased with the square root of the number counted. An increase such as this follows the "law of diminishing returns" and makes the counting of a few hundred grains the most practical. According to Dryden, a count of 4549 grains is required for 1% accuracy, but 5% accuracy can be obtained by counting only 200. Taking this into consideration, a count of 200 grains was considered adequate for the purpose of this investigation.

Heavy mineral analyses were made of twenty samples representing 18 of the best outcrop locations. These were Locations 0, 2, 5A, 5C, 11, 13B, 15, 16, 18, 20, 22, 25A, 27B, 29, 31, 34, 36, and 37.

SEDIMENTARY ENVIRONMENT

Introduction

The Atlantic Coastal Plain contains sediments that correspond to those of the Gulf Coastal Plain, although the thickness is moderate by comparison. Off-shore, however, geophysical investigations (Ewing, Worzel, Steenland, and Press, 1950) have indicated that the basement beneath Cretaceous or possible Jurassic descends rapidly to a depth of 16,000 feet below sea level, and then rises again to a depth of 14,000 feet below sea level near the edge of the continental shelf.

Kay (1951) called this structure a "paraliageosyncline" of possible

Jurassic and Cretaceous sediments, similar to a miogeosyncline, but differing in that it marks a new cycle of subsidence in a region that has passed through an orogenic and plutonic history after having been a eugeosynclinal belt of the same general trend. Unfortunately, the sediments of an undeformed structure of this kind are not generally well exposed, and are accessible only in limited outcrops, in wells in the shallowest parts, or by geophysical means. Until off-shore drilling is undertaken on the Atlantic Coast, a more detailed study of the Atlantic Coast paraliageosyncline will be difficult.

In discussing tectonic control of lithologic associations, Dapples, Krumbein, and Sloss (1948) described the general characteristics of stable shelves and their deposits. The Atlantic Coastal Plain was used as an example of a stable shelf, where the shore line represents a boundary between aqueous and subaerial conditions, but where the general profile of the land surface continues beneath the water with only slight modification. The stable shelf implied an area of epeirogenic movement in both shelf and source area resulting in a supply of detritus small in comparison with the area of the shelf.

Lithology and Texture

The predominant lithology of the Mount Laurel and Wenonah sands in outcrop is a massive or horizontally bedded, medium to fine, well sorted, slightly glauconitic and micaceous quartzose sand. This lithology is fairly uniform along the entire length of the outcrop area, suggesting uniform deposition of a shelf environment rather than the varied deposits of a fluviatile origin. The lithology of the inliers near Holmdel is quite different. Here the formation becomes too argillaceous for conventional sieving, suggesting an embayment of deeper water. The curving trend of the outcrop in that area supports this conclusion.

Well samples show considerable variation in glauconite content. In wells number 1 (Atlantic City) and 2 (Fort Dix), glauconite constitutes about 50% of the sample. In well number 3 (Lakewood), glauconite drops to about 25% and in well number 4 (Neptune Township) and 5 (Pine Valley) the samples are only slightly glauconitic. The high glauconite content in well numbers 1, 2 and 3 could indicate water deeper than wave, tidal, and current action, but still neritic, with slightly reducing conditions at least at the site of origin within the enclosing sediments, if not in the bottom waters (Cloud, 1955).

Mechanical analysis of the Mount Laurel and Wenonah outcrop samples revealed that the median grain size varied from .12mm to

.40 mm, or fine to medium sand. The mode usually occurred between .35 mm and .25 mm, but there are several exceptions where the mode occurs to the right or to the left of this. The mode of the well samples was extremely variable and the median grain size ranged from .13 to .35 mm, or fine to medium sand. Fine sand occurred in well numbers 1, 3, and 4, and medium sand occurred in well numbers 2 and 5. All of the outcrop and well samples are extremely well sorted, their coefficients varying from 1.16 to 1.76 in the outcrops and from 1.34 to 1.69 in the wells. Skewness values ranged from .62 to 1.15 in the outcrop samples, having equal distribution on each side of unity. All of the well samples, except number 2, had skewness values exceeding unity, or coarse admixtures exceeding the fine admixtures. Krumbein and Pettijohn (1938) show a median of .30 mm, a sorting coefficient of 1.22, and a skewness of .96 for beach sand. These values are comparable to those of the Mount Laurel and Wenonah sands.

Inman (1949) studied the transportation of sediments and noted that the threshold velocity, or the critical velocity at which a particle begins to move owing to the drag force of the fluid, is smallest for particles of fine sand size, and increases for particles smaller and larger than this size. The threshold velocity is considerably greater than the settling velocity for particles smaller than fine sand. Thus, once a particle begins to move it will tend to be transported in suspension rather than by traction.

The cumulative curves usually show a break in slope near 1/8 mm with a steeper slope to the left, or better sorting, than to the right where considerable variation occurs in the material finer than 1/8 mm. Groot (1955) has shown similar curves for the Upper Cretaceous marine formations of Delaware. Groot suggested that the two parts of his curves correspond to the traction and suspension load respectively. He stated:

> "Generally the cumulative curves show fine to very fine sand with varying amounts of silt and clay, indicating transportation and deposition of tractional material of relatively small grain size, and in addition, deposition of a fine suspension load. Thus, the currents must have been strong enough to move medium sand, and in some cases, small quantities of coarse sand, while velocities must have decreased periodically in order to deposit the suspension load. Such conditions exist where tidal currents are present, and, consequently, where flood and ebb currents alternate with periods of slack water in between. Thus, the medium to fine sands were deposited by tidal currents, and the silts and clays during slack water."

Mechanical analysis therefore indicates that the Mount Laurel and Wenonah sands for the most part were deposited in a near-shore marine environment, where flood and ebb tides fluctuated with periods of slack water.

Reed (1960) found evidence of a similar near-shore marine environment in studying the Englishtown formation of New Jersey. In addition, local deposits of cross-bedded sand and silt with abundant lignite and marcasite suggested a lagoonal environment in some areas.

A comparison of median grain size was made between several lithologies which were typical Mount Laurel and several which were typical Wenonah:

Typical Mount Laurel Lithology		Typical Wenonah Lithology	
Locality 5A	.31 mm	Locality 5C	.12 mm
18	.27	13B	.18
25A	.26	16	.22
27A	.36	25B	.16
33	.33	27B	.15

It is obvious that the Wenonah lithology is usually finer grained than the Mount Laurel lithology. The Mount Laurel can therefore be classified as a medium sand, and the Wenonah as a fine sand, on the basis of these localities. A comparison of the sorting coefficients and skewness values of the two units showed no consistency. No consistency was found in the statistical values of the remaining localities to warrant separation on this basis. Localities along the inner edge, or base, of the outcrop, with comparable elevations, and presumably Wenonah, had median grain sizes just as large as those along the outer edge, or top of the outcrop, and presumably Mount Laurel. Apparently the fine sand lithology of the Wenonah only occurs locally, and is a facies of the medium sand lithology which so closely resembles the Mount Laurel.

Paleontology

The scarcity of fossils in the Mount Laurel and Wenonah sands is not surprising, since constant reworking of shelf sediments could result in gradual elimination of organic remains. Post-depositional weathering and ground water action could also play a part in explaining the absence of some fossils.

Weller (1907) recorded a list of 54 species, collected from the

Wenonah at a marl pit (no longer accessible), 1 mile southeast of Crawford's Corner. This is one of the few localities of the formation from which fossils have been secured. These fossils were all more or less imperfect internal casts and moulds, and aside from the species recognized there were many others, which were too imperfectly preserved to be identified. Weller believed that the entire fauna did not fall far short of 100 species, including the unidentified forms. This fauna appeared to be closely allied to the older Woodbury formation, and contained comparatively few species in common with the subjacent Marshalltown and the Mount Laurel. A long list of fossils has been recorded from the shell bed at the base of the Navesink formation. According to Weller (1907), this shell bed also occurs within the Mount Laurel, and the fauna representing both formations constitutes a unit. The fauna is closely allied to that of the Marshalltown, and contains a distinctive assemblage, chief among which is the cephalopod Belemnitella americana and the brachipod, Choristothyris plicata.

No erosion surfaces or disconformities were observed at the base or top of the Mount Laurel and Wenonah sands, and apparently the boundaries are transitional, representing continuous deposition. A regression of the sea apparently took place at the end of the deposition of the deep-water Marshalltown clay-marl. As the sea withdrew, and the water became shallower, the fine sands of the Wenonah were deposited, although locally there was deposition of a medium sand facies. At the shallowest stage, the medium sands of the Mount Laurel were deposited. Following this was the transgression of the sea, and deposition of the deep-water Navesink clay and sand.

Heavy Minerals

The percentages of heavy minerals range from .40% at Locality 15 to 1.42% at Locality 18. The proportion of opaque minerals ranged from a count of 228 grains for Locality 15 to 1058 grains for Locality 31, as compared to a count of 200 nonopaque grains for each locality. The heavy mineral suite of the Mount Laurel and Wenonah sands contains andalusite, chloritoid, epidote, garnet, kyanite, mica, rutile, sillimanite, staurolite, tourmaline, zircon, and hornblende, and account for the bulk of the nonopaque minerals. This persistent group of minerals occurs in varying proportions throughout the formation except for the local absence of garnet, epidote, zircon, or hornblende at several localities.

L. and C. Dryden (1959 and in press) named two suites of heavy minerals as typical of the Atlantic Coastal Plain--the restricted suite and the full suite. The restricted suite contains andalusite, kyanite, rutile, sillimanite, staurolite, tourmaline and zircon. The full suite contained, in addition to the above, chloritoid, epidote, garnet, and hornblende. North of Virginia, the restricted suite occurred in the nonmarine Cretaceous, and the full suite occurred in the marine Cretaceous. Groot (1955) found the same relationship in the Cretaceous of Delaware. Therefore, the heavy mineral suite of the Mount Laurel and Wenonah sands is a full suite, and is indicative of a marine environment.

Petrologic investigations have indicated that certain minerals are characteristic of particular igneous or metamorphic rocks. Pettijohn (1957) summarized the detrital mineral suites characteristic of different source rocks. The Upper Cretaceous Mount Laurel and Wenonah sands could have been derived from metamorphic rocks of the Piedmont or New England Prong, and from igneous and sedimentary rocks of the Triassic Lowland, or Valley and Ridge Province. In addition to the above possible source areas, the older Cretaceous sediments such as the Englishtown, Merchantville, or Raritan could have played a part in supplying heavy minerals to the Mount Laurel and Wenonah sediments.

A comparison of heavy mineral counts was made between several lithologies which were typical Mount Laurel (Localities 5A, 18, 25A, 27A, and 29) and several which were typical Wenonah (Localities 5C, 13B, 16, and 27B). Both lithologies were found to contain the same mineral species, and no consistency was found in their relative proportions to warrant separation on this basis. The same inconsistency was found in a comparison of the total heavy mineral percentages and the relative proportions of opaque to nonopaque minerals.

SUMMARY

The predominant lithology of the Mount Laurel and Wenonah sands in outcrop is a massive or horizontally bedded, medium to fine, well sorted, slightly glauconitic and micaceous quartzose sand. This lithology is fairly uniform along the strike of the outcrop and suggests a uniform deposition of a shelf environment rather than the varied deposits of a fluviatile origin. The lithology of the inliers near Holmdel is quite different. Here the formation becomes too argillaceous for conventional sieving, and along with the curving trend of the out crop in that area, indicates an embayment of deeper water. Down dip to the southeast, the formation becomes very glauconitic and indicates deeper water unaffected by wave, tidal or current action. Slightly reducing conditions probably existed at the site of origin within the enclosing sediments, if not in the bottom waters.

Mechanical analysis of the outcrop samples, through interpretation of statistical values and cumulative curves indicate a near shore marine environment. Transportation and deposition of the coarser material seems to have been by traction whereas the finer sediments represent a suspension load, and suggest conditions where flood and ebb tides fluctuated with periods of slack water. A comparison of statistical values showed that the Mount Laurel was coarser grained than the Wenonah at several localities where the lithologies were distinctive. On the basis of these localities the Mount Laurel is a medium sand, and the Wenonah is a fine sand, but inconsistency in the statistical values of the remaining localities rendered separation on this basis impossible. The fine sand lithology of the Wenonah only occurs locally, and appears to be a facies of the medium sand lithology which so closely resembles the Mount Laurel.

A regression of the sea apparently took place at the end of the deposition of the deep-water Marshalltown clay-marl. As the sea withdrew, and the waters became shallower, the fine sands of the Wenonah were deposited locally. At the shallowest stage, the medium sands of the Mount Laurel were deposited. Following this was the transgression of the sea, and deposition of the deep-water Navesink clay and sand.

The heavy mineral suite of the Mount Laurel and Wenonah sands is a full suite, and is indicative of a marine environment. The same heavy minerals occur in varying proportions along the strike of the outcrop. Both units contain the same suite, and no consistency was found in the mineral frequencies to warrant separation on this basis.

The metamorphic rocks of the Piedmont or New England Prong, and Igneous and sedimentary rocks of the Triassic Lowland, or Valley and Ridge Province, as well as the older Cretaceous sediments, all could have played a part in supplying heavy minerals to the Mount Laurel and Wenonah sands.

ACKNOWLEDGMENTS

The writer wishes to thank Oswald C. Farquhar and other members of the Geology Department of the University of Massachusetts who directed the research and supervised the writing of this paper.

The project was suggested by Horace G. Richards of the Academy of Natural Sciences of Philadelphia and the University of Pennsylvania, who was generous with his time and interest. He checked all localities in the field and critically read the preliminary copy of this manuscript. To Lincoln and Clarissa Dryden and Juliet Reed of the Department of Geology at Bryn Mawr College, special thanks are due for technical assistance with the heavy mineral work. The Departments of Geology of the University of Pennsylvania, Bryn Mawr College, and Academy of Natural Sciences, generously furnished their laboratory facilities. Well samples were provided by the Geology Department of the Academy of Natural Sciences. Kemble Widmer, State Geologist of New Jersey, supplied the writer with topographic maps for field use and assisted in other ways.

This work was made possible by financial aid from the Coastal Plain Fund and the Jessup Fund of the Academy of Natural Sciences, and the New Jersey Geological Survey.

REFERENCES

Cloud, P. E., 1955, Physical Limits of Glauconite Formation: Bull. Amer. Assoc. Petrol. Geol., v. 39, p. 484-492.

Dapples, E. C., Krumbein, W. C., and Sloss, L. L., 1948, Tectonic Control of Lithologic Associations: Bull. Amer. Assoc. Petrol. Geol., v. 32, p. 1924-1947.

Dryden, Lincoln, 1931, Accuracy in Percentage Representation of Heavy Mineral Frequencies: Nat. Acad. Sci. Proc., v. 1, p. 233-238.

Dryden, Lincoln and Clarissa, 1959, Heavy Minerals from the North Carolina Coastal Plain: Proc. Pennsylvania Acad. Sci., v. 33, p. 185-194.

Dryden, Lincoln and Clarissa, in press, Atlantic Coastal Plain Heavy Minerals: A Speculative Summary, Proceedings 20th International Geological Congress.

Ewing, M., Worzel, J. L., Steenland, N. C., and Press, F., 1950, Geophysical Investigations in the Emerged and Submerged Atlantic Coastal Plain: Bull. Geol. Soc. Amer., v. 61, p. 877-892.

Groot, Johan J., Organist, Donna M., and Richards, Horace G., 1954, The Marine Upper Cretaceous Formations of the Chesapeake and Delaware Canal: Delaware Geological Survey, Bull. 3, 64 p.

Groot, Johan J., 1955, Sedimentary Petrology of the Cretaceous Sediments of Northern Delaware in Relation to Paleographic Problems: Delaware Geological Survey, Bull. 5, 157 p.

Inman, Douglas, 1949, Sorting of Sediments in the Light of Fluid Mechanics: Jour. Sed. Pet., v. 19, p. 51-70.

Kay, George M., 1951, North American Geosynclines: Geol. Soc. America Mem. 48, 143 p.

Krumbein, W. C. and Pettijohn, F. J., 1938, Manual of Sedimentary Petrography: Appleton-Century-Crofts, New York, 549 p.

Owens, J. P. and Minard, J. P., 1960, The Geology of the North-Central Part of the New Jersey Coastal Plain: Johns Hopkins Univ. Studies in Geol., no. 18, 45 p.

Pettijohn, F. J., 1957, Sedimentary Rocks; 2nd ed., Harper Brothers, New York, 713 p.

Reed, Juliet, 1960, Heavy Minerals of the Englishtown (Cretaceous) Formation of New Jersey: Proc. Pennsylvania Acad. Sci., v. 34, p. 147-154.

Richards, H. G., 1945, Subsurface Stratigraphy of the Atlantic Coastal Plain between New Jersey and Georgia: Bull. Amer. Assoc. Petrol. Geol., v. 29, p. 885-955.

Trask, P. D., 1932, Studies of Recent Marine Sediments Conducted by the American Petroleum Institute: National Research Council, Bulletin 89, Report Com. Sed. 1930-32, p. 60-67.

Weller, S., 1907, A Report on the Cretaceous Paleontology of New Jersey: Geological Survey of New Jersey, 682 p.

Table 1

Upper Cretaceous Formations of New Jersey

Stage	Group	Formation	Lithology	Thickness in outcrop
Maestrichtian	Monmouth Group	Red Bank sand	Yellow and reddish-brown sand	30-130'
Maestrichtian	Monmouth Group	Navesink formation	Glauconitic clay and sand	25-40'
Maestrichtian	Monmouth Group	Mount Laurel sand	Medium to coarse sand, some glauconite	10-60'
Campanian	Matawan Group	Wenonah Formation	Fine to medium sand	25-35'
Campanian	Matawan Group	Marshalltown formation	Black sandy clay to argillaceous greensand marl	30-40'
Campanian	Matawan Group	Englishtown formation	White and yellow sand; micaceous and slightly glauconitic	20-140'
Campanian	Matawan Group	Woodbury clay	Black micaceous clay; non-glauconitic	50'
Campanian	Matawan Group	Merchantville formation	Black glauconitic micaceous clay	50-60'
Santonian				
Coniacian		Magothy formation	Alternating dark colored clay and light colored sand, considerable glauconite	25-175'
Turonian				
Cenomanian		Raritan formation	Alternating varicolored sand and clay	150-300'

THE SEDIMENTS OF THE BEAUFORT INLET AREA, NORTH CAROLINA

by

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ABSTRACT

Two hundred and two bottom samples were collected from the Beaufort Inlet area to determine the distribution of sediments and the relation of the total sediment to the inlet environment. The channel, gorge, and zone of wave action environments were distinguished on the basis of the bottom topography and currents.

Six types of bottom sediment, predominantly sand decreasing in size from the gorge, were identified on the basis of size range and mode, phi median diameter, and one percentile diameters.

Graphic comparison of median diameter, one percentile diameter, skewness, sorting, and kurtosis showed that the sediments fell into groups which correlated with the distinct physical environments.

Channel sediments were coarse to very fine, poorly sorted sands. The gorge sediments ranged from pebbles to fine sand and had a characteristically high carbonate content. The zone of wave action sediments were finer and better sorted than the channel and gorge sediments.

INTRODUCTION

The study of the Beaufort Inlet was undertaken to determine the patterns of sediments distribution and to delineate the environment of deposition in the vicinity of a tidal inlet.

Beaufort Inlet, about 1.5 miles wide, is located on the "Outer Banks" of North Carolina 10 miles northwest of Cape Lookout and 3 miles southeast of Morehead City (Figure 1). The investigated area measures approximately 10 miles in an east-west direction and 5 miles in a north-south direction, covering an area of 50 square miles.

The area is situated on a Recent wave-built prograded barrier beach veneered with sands, silts and clays which seem to be continuous with the surficial deposits of the adjacent Coastal Plain.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the help and able assistance of the staff of the University of North Carolina Institute of Fisheries Research in Morehead City, North Carolina, the Fort Macon Coast Guard Station, and Roy L. Ingram of the University of North Carolina for his helpful suggestions and criticisms.

METHODS

The samples and field observations of the Beaufort Inlet area were taken during a seven day period in the summer.

Bottom samples (Figure 2) were taken with a Petersen grab sampler and plotted on the Beaufort and Harkers Island Quadrangle topographic maps with the aid of the U. S. Coast and Geodetic Survey Chart No. 420.

In the preliminary laboratory investigation of each sample, estimates were made of grain size range and mode, abundance of shell fragments and heavy minerals, and sphericity and roundness.

Seventy-six samples were washed for size analysis. After dispersal of the sample, the sand, silt and clay were separated for analysis as described by Krumbein and Pettijohn (1938, p. 166-167).

Percentage of soluble carbonate material was determined on 53 samples. Coarse-fraction analysis was carried out on all of the semi-detailed size analysis.

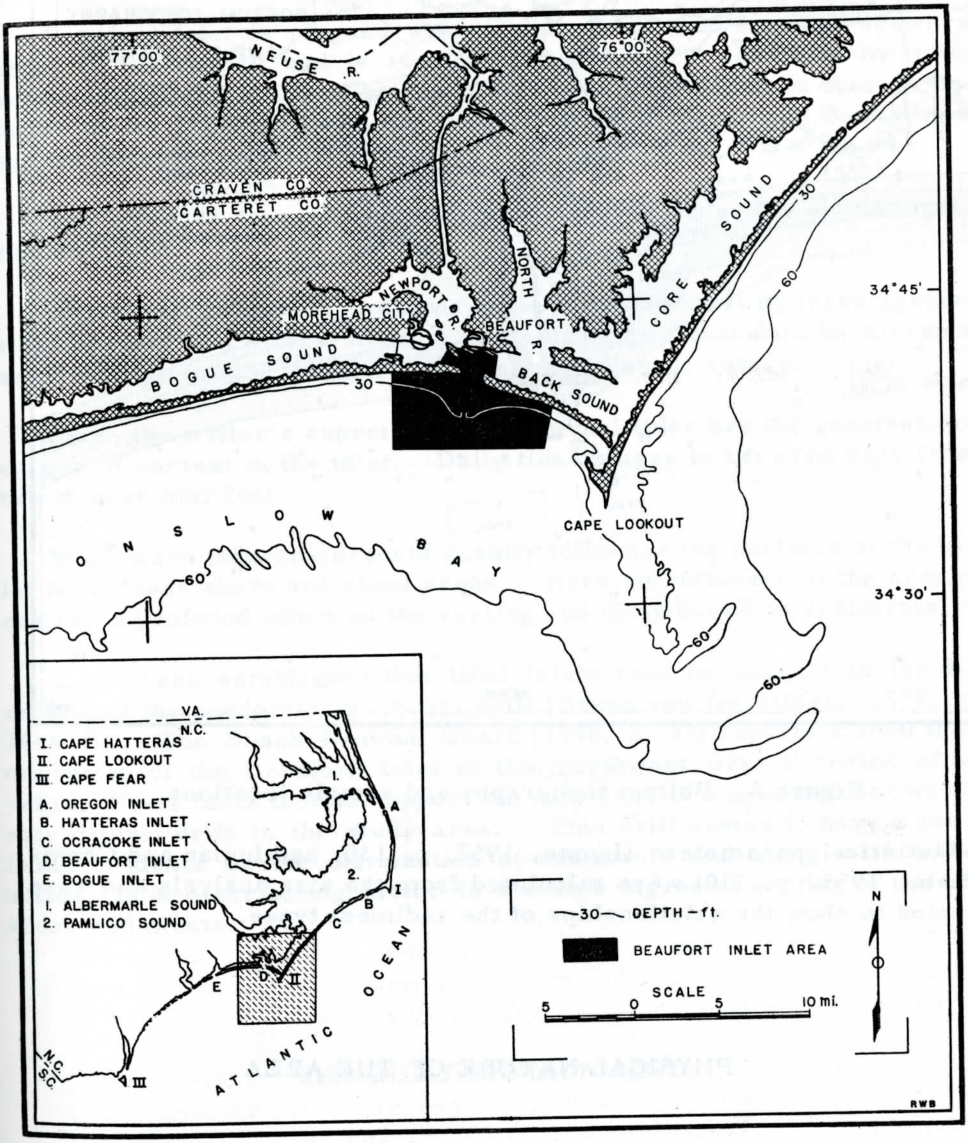

Figure 1. Index map of the area studied.

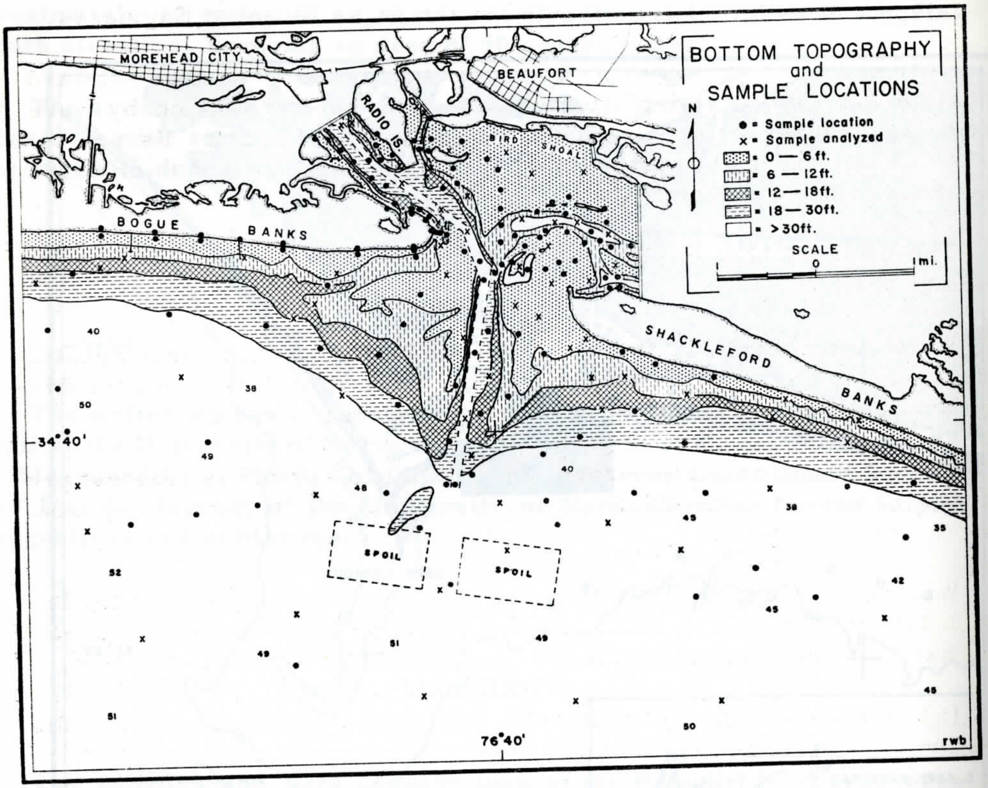

Figure 2. Bottom topography and sample locations.

Statistical parameters (Inman, 1952, p. 130, and Inman and Chamberlain, 1955, p. 110) were calculated from the size analysis and were selected to show the relationships of the sediment types.

PHYSICAL NATURE OF THE AREA

In the Beaufort Inlet area the shoreline is a clean sand beach sloping gently from the foreslope of the dunes to the foreshore or beach face. The inshore breaker zone is characterized by a longshore-trough separating the beach and longshore-bar. A rather abrupt increase in slope occurs as one passes across the longshore bar and continues to a distance of about one mile off shore, where the slope becomes gentle and concomitant with the slope of the continental shelf.

Three distinct topographic regions earmark the study area: channel, shoal, and offshore. The channel regions are 300-400 feet wide and are dredged for purposes of navigation (Figure 2). They are dredged to a depth of 30 feet and are maintained by the Army Corps of Engineers.

Beaufort Inlet is plagued with two hazardous shoals. The seaward shoal is fan-shaped and is stunted in its seaward extension by wave action and littoral drift. The sound side shoal is difficult to discern because of its continuity with the shallow shoals of Bogue and Back Sound and the Newport and North Rivers.

The offshore topography is characteristic of the gently sloping continental shelf.

Water movements in the area seem to be manifest by three agents: tides, waves, and littoral drift. Little or no significant data on currents are available for the Beaufort Inlet and its adjacent waters.

From the writer's experience, the diurnal tides are the greatest producers of current in the inlet. Daily tidal ranges in the area vary from two to over four feet.

Wind wave induced currents greatly influence the portions of the Inlet in the near shore and shoal areas. Here the influence of the breakers has a profound effect on the sorting and distribution of sediments.

It has been established that tidal inlets tend to migrate in the direction of the predominant littoral drift (Bruun and Gerritsen, 1958, p. 1644-4). The Beach Erosion Board (1948, p. 33) reports a 1600 foot migration of the Beaufort Inlet to the northwest over a period of 62 years. These facts tend to support the existence of a predominant westerly littoral drift in the study area. This drift seems to have a profound influence on the distribution of sediments and along with wave action, is a contributing factor to the high degree of sorting of the off shore sediments.

THE INLET ENVIRONMENT

Three major physical environments are recognized in the Beaufort Inlet area. The channel, gorge, and zone of wave action environments each have distinctive topographic and current relationships which define their boundaries.

Channel Environment

This environment is defined by U-shaped channels averaging 30 feet in depth cutting into the shallow Beaufort Inlet tidal delta and by current velocities of more than 2 knots. Marginal shoals or tidal flats surround the channels.

Gorge Environment

The gorge of the inlet is defined as the zone of minimum width between the Bogue and Shackleford Banks. The gorge is a part of the channel which in part exceeds 40 feet in depth (Army Corps of Engineers, unpublished chart, 1958). Current velocities appear much greater in the gorge than in the channel during tidal changes. This phenomenon is facilitated by the funneling of the tidal ebbing and flooding currents.

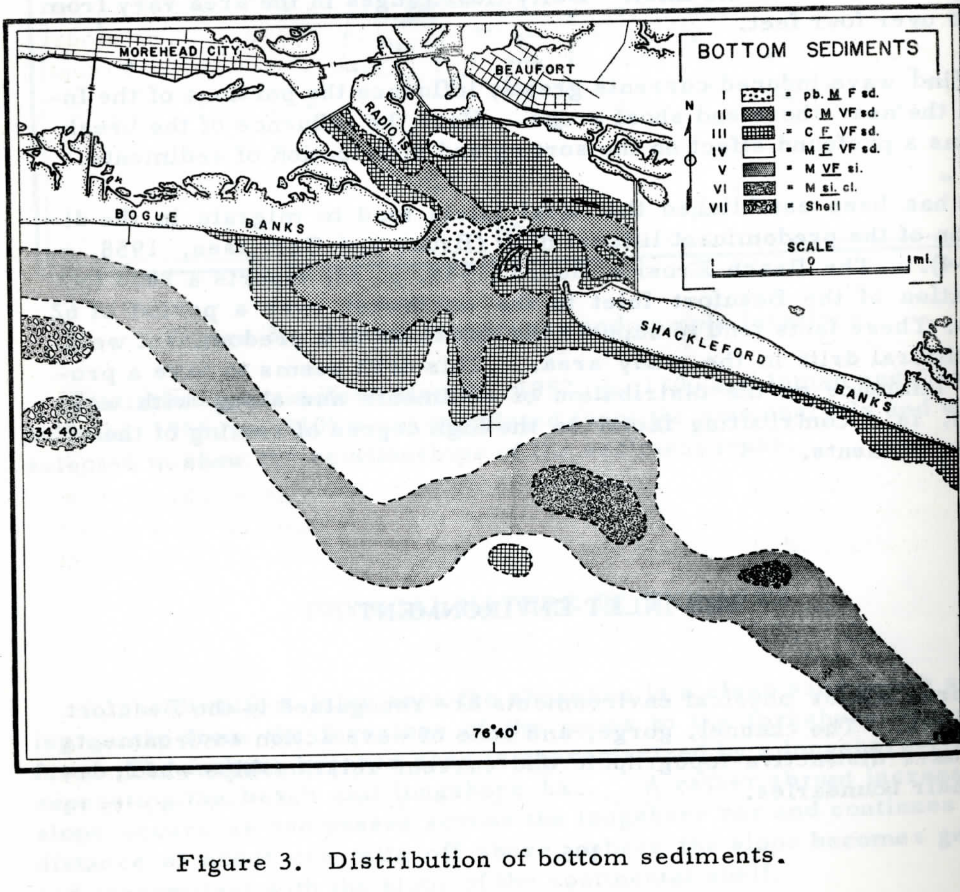

Figure 3. Distribution of bottom sediments.

Zone of Wave Action

The zone of wave action ranges from shallow shoal and foreshore beach to relatively deep water. It is affected primarily by the action of surface waves.

SEDIMENTS

Gross Lithology

Seven types of bottom sediments are found in the Beaufort Inlet area. Five of the sediment types are predominantly sand, decreasing in size away from the gorge environment (Figure 3). Type VI sediments are atypical in comparison with other sediments in that they are unusually fine and discontinuous in distribution. Unconsolidated beds of whole and broken shells compose Type VII sediments. Table 1 compares the size range and modal class of the six sediment types. The modal class comprises greater than 40% by weight of the total sample except in Type I.

Table 1

Size range and mode of six sediment types in the Beaufort Inlet area

TYPE	SIZE			ENVIRONMENT
	COARSEST	MODE	FINEST	
I	pebble	medium sd	fine sd	gorge
II	coarse sd	medium sd	v. fine sd	channel
III	coarse sd	fine sd	v. fine sd	zone of wave action
IV	medium sd	fine sd	v. fine sd	zone of wave action
V	medium sd	v. fine sd	silt	zone of wave action
VI	medium sd	silt	clay	zone of wave action

Size Parameters

Figure 4 shows the distributional patterns of the phi median diameters of the sediments. It is notable that there is a distinct decrease in median diameter away from the gorge environment. This decrease in size is correlative with the decrease in competency of the currents to winnow out the fine admixture of the sediment.

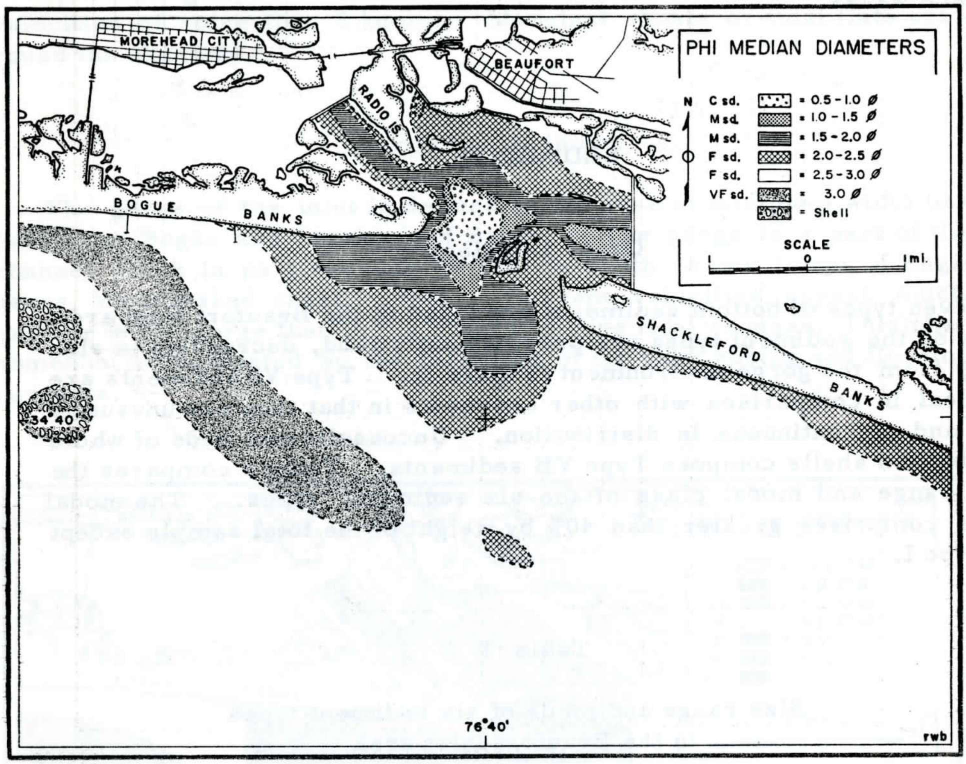

Figure 4. Distribution of phi median diameters

Five parameters may be used to show a relationship of the sediments to the particular environment already delineated according to bottom topography and currents.

Figure 5 shows the comparison between the one percentile diameter and the phi-median diameter (Passega, 1957, p. 1952-1956). The gorge and channel sediments represent sediments transported in traction by bottom currents (Passega, 1957, p. 1974). The zone of wave action sediments correspond with Passega's typical beach sediments.

The sorting and skewness comparison (Figure 6) facilitates a separation of the gorge and channel sediments from the zone of wave action sediments. The gorge and channel sediments are moderately to poorly sorted and negatively skewed. Moderate to well sorting and nearly sym-

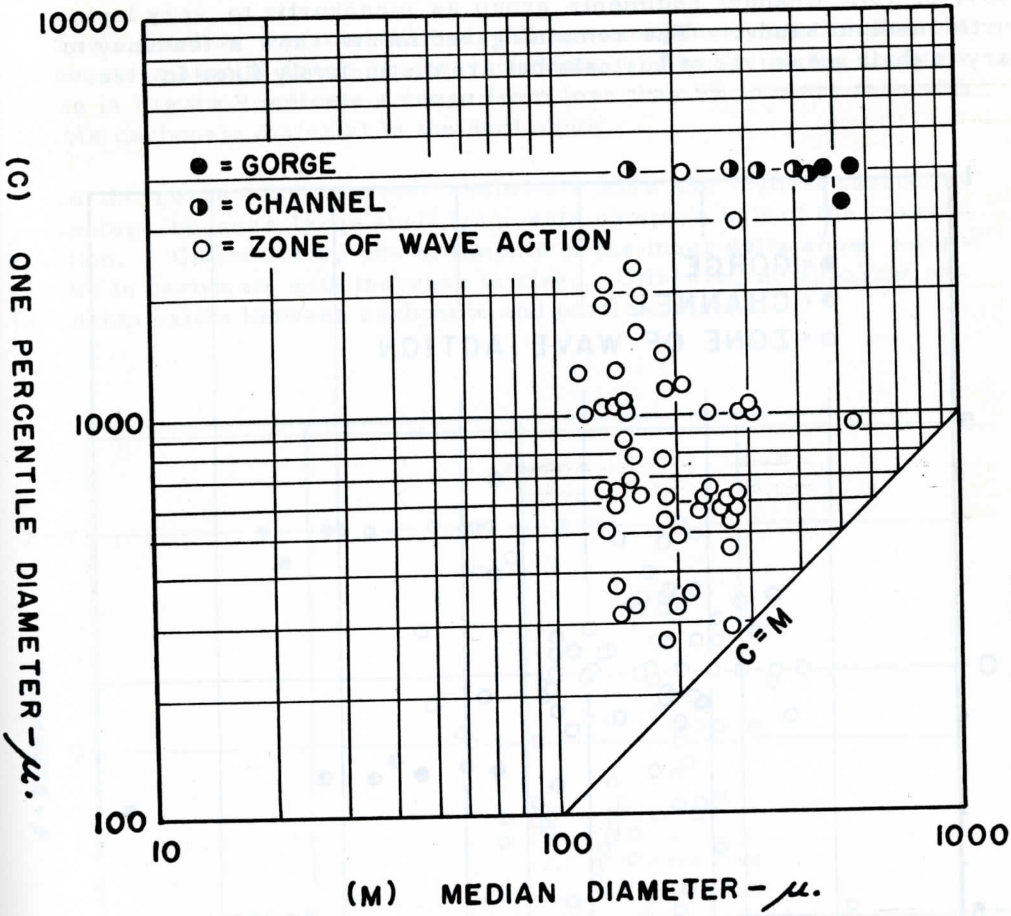

Figure 5. Comparison of one percentile and median diameters.

metrical skewness typify sediments of the wave action zone (Folk and Ward, 1957, p. 14).

A characteristic attribute of the gorge and channel sediments is their pronounced negative skewness. Figure 7 shows a segregation of the sediments into coarse negatively skewed, and medium and fine negatively skewed gorge and channel type sediments, respectively. In contrast, the zone of wave action sediments are predominately fine in median diameter and have nearly symmetrical skewness.

Perhaps the clearest representation of the association of certain sediments with the physical environments is shown by comparing median diameter with the kurtosis (Figure 8). The gorge sediments group as a coarse mesokurtic to platykurtic assemblage (Folk and Ward, 1957, p. 15). Channel sediments group as mesokurtic to very leptokurtic medium sands. The remaining sediments show a tendency to vary in their measures of kurtosis but are distinctively finer in size.

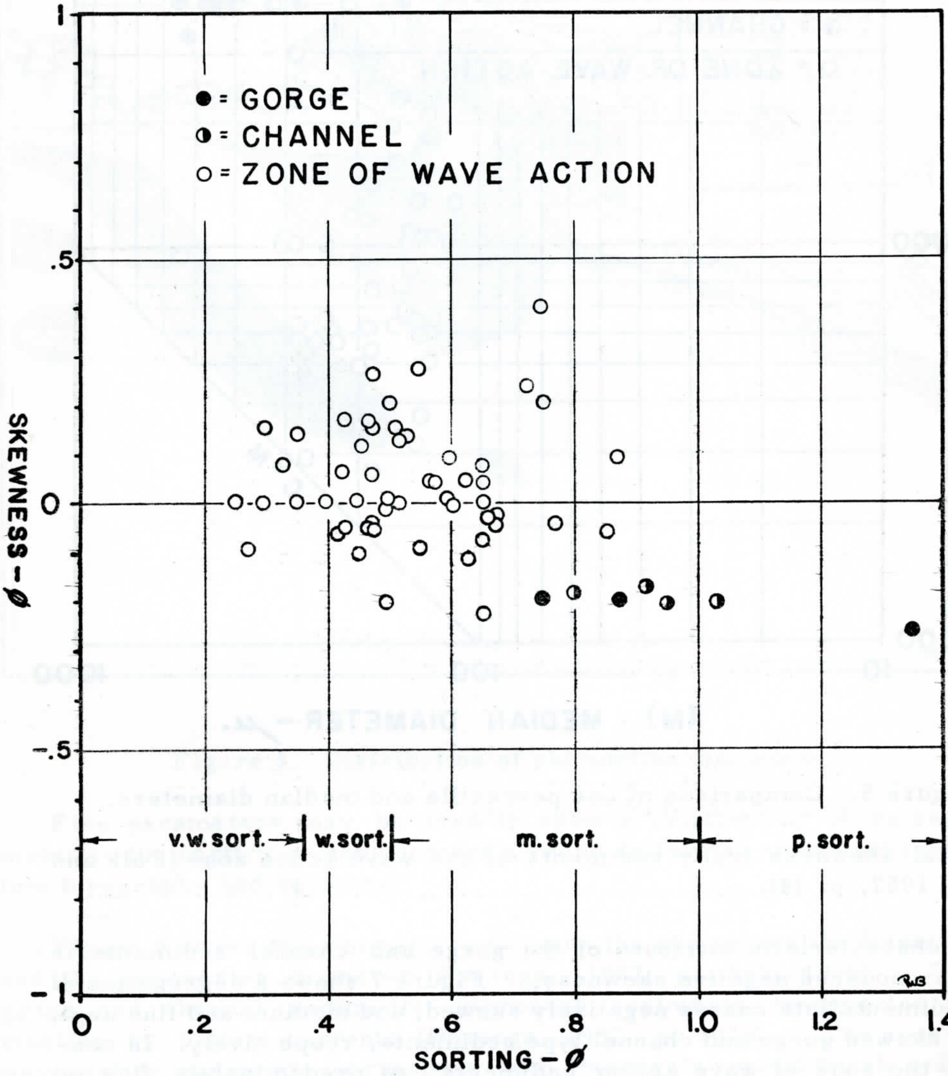

Figure 6. Comparison of sorting and skewness.

Calcium Carbonate

Shell detritus was the only significant component of the soluble carbonate material found in the sediments. Results of the analysis shown in Figure 9 indicate a range from less than 5% to more than 40% soluble carbonate material in the sediments.

In the gorge, the coarsest sediments have the highest carbonate percentage because large shell fragments compose half of the coarse-fraction. Collectively, the sediments of the inner delta show an increase in carbonate with increase in size. Offshore, no apparent relationship exists between carbonate and particle size.

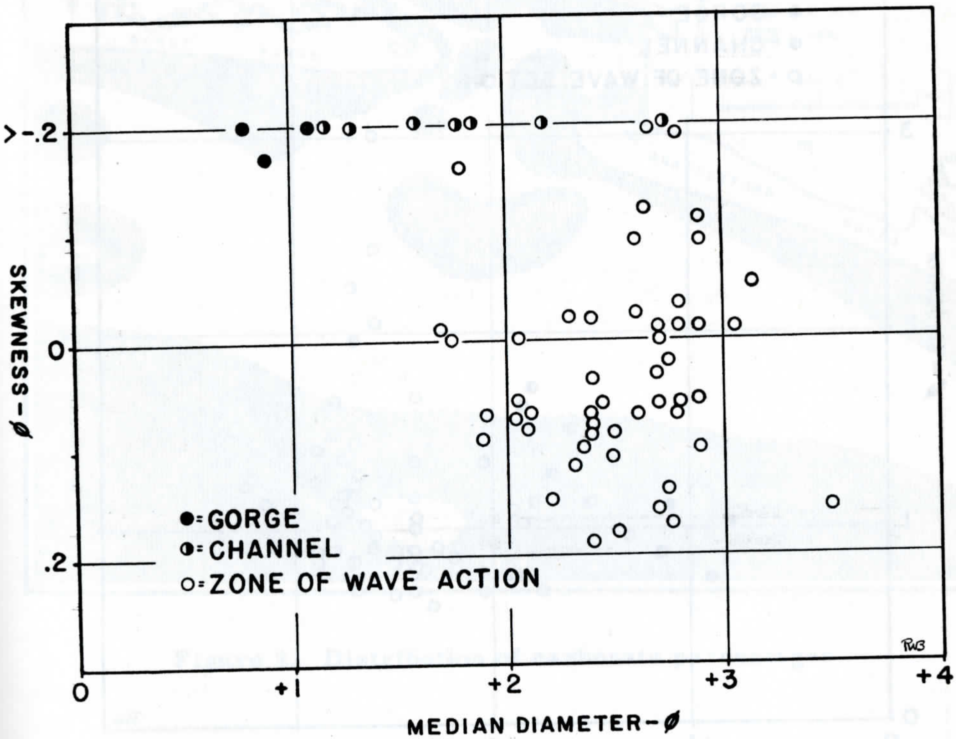

Figure 7. Comparison of skewness and median diameters.

RESULTS

A sedimentary environment is established by relating the properties of a given number of sediments with a physically distinct environment. In the Beaufort Inlet area, three characteristic deposits are delineated according to size, sorting, skewness, kurtosis, and percentage of carbonate.

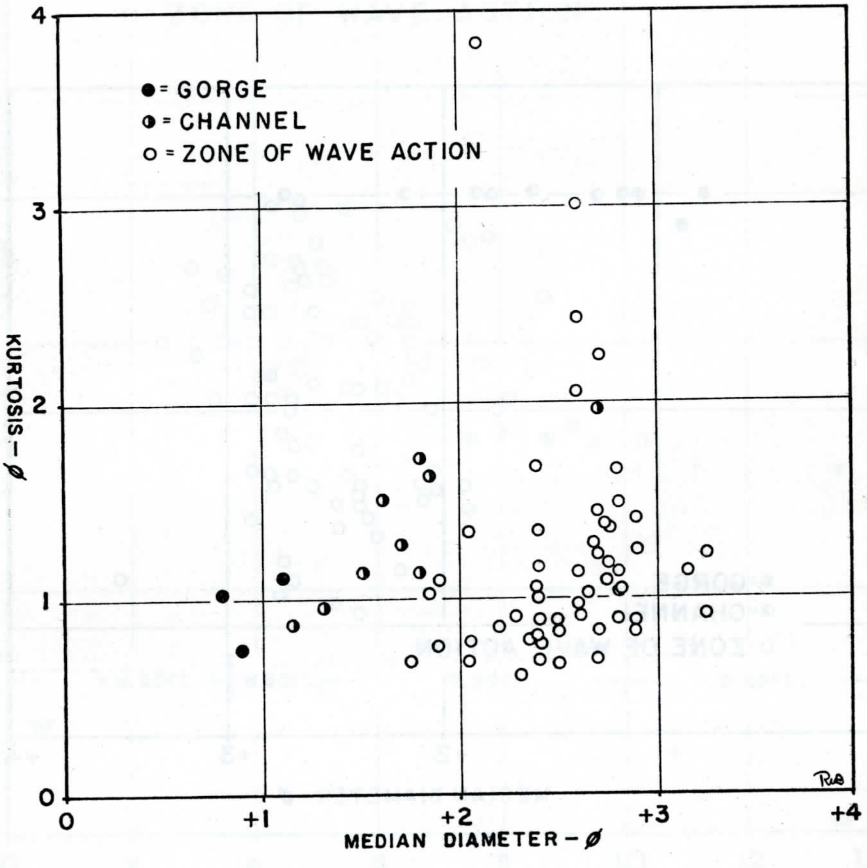

Figure 8. Comparison of kurtosis and median diameters

Channel

The relatively high velocities of the tidal currents in the U-shaped channels cause an accumulation of lag sediments ranging from coarse to very fine sand. The variable tidal current velocity resulting from the full to slack components of the diurnal tides accounts for the moderate to poor sorting of the channel sediments. The sorting configuration results in a mesokurtic to very leptodurtic expression of the size distribution. Ten to 20% soluble carbonate material exists in the channel sediments.

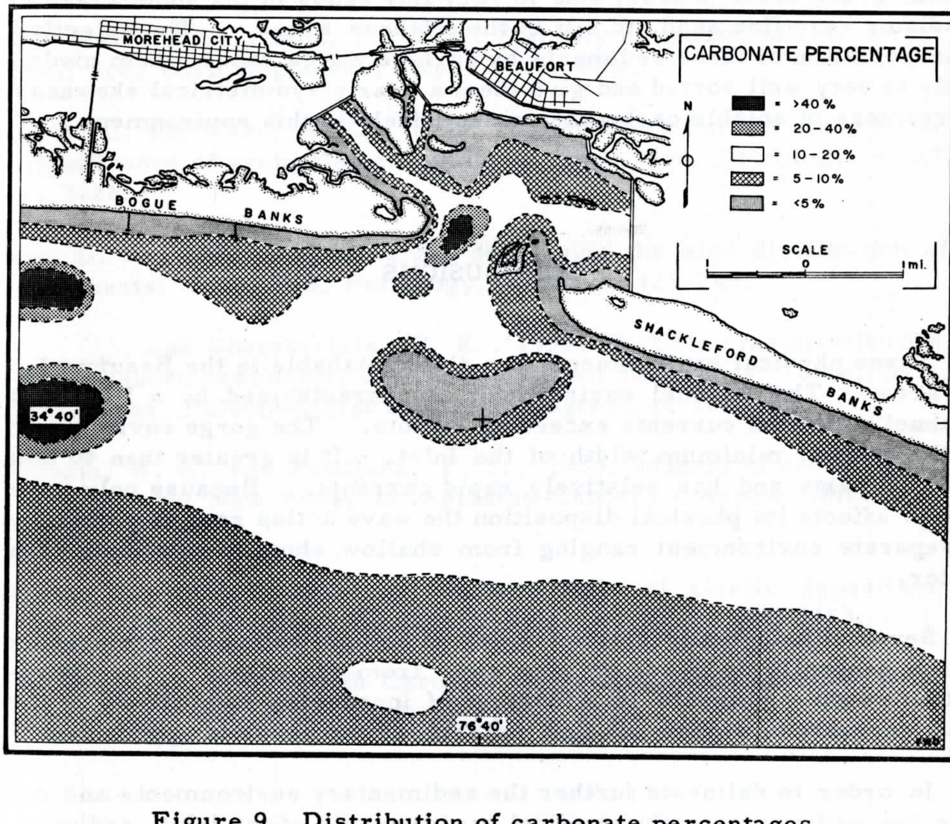

Figure 9. Distribution of carbonate percentages

Gorge

The high current velocity of the gorge gives rise to the accumulation of coarse, poorly sorted, negatively skewed, high carbonate sands. Physically, the gorge has a greater depth and more rapid tidal currents than does the channel. Diagnostic features of the gorge sediments are their coarseness, mesokurtic and platykurtic peakedness, and their very high carbonate content.

Zone of Wave Action

Finer size, better sorting, symmetrical skewness, and lower percentage of shell debris, are attributes which distinguish the zone of wave action sediments from those of gorge and channel. The sediments grade from coarse, fine to very fine sands in the shoal areas to medium, very fine sand, to silt in the offshore areas. The selective transportation of these sediments by surface waves render them moderately to very well sorted and give them a nearly symmetrical skewness. Percentage of soluble carbonate varies widely in this environment.

CONCLUSIONS

Three physical environments are distinguishable in the Beaufort Inlet area. The channel environment is characterized by a U-shaped channel with tidal currents exceeding 2 knots. The gorge environment is the point of minimum width of the inlet. It is greater than 40 feet deep in parts and has relatively rapid currents. Because only wave action affects its physical disposition the wave action zone is primarily a separate environment ranging from shallow shoal to relatively deep water.

Seven lithologically distinct types of bottom sediments are present which generally decrease in size away from the gorge. The distribution of the sediments is a function of increasing competency of the tidal currents to winnow out fine material as the gorge is approached.

In order to delineate further the sedimentary environments and relate the sediments to the physical environments of the inlet, sedimentary parameters are compared. This comparison facilitates a segregation into channel, gorge, and zone of wave action sedimentary environments. A comparison of median diameter and kurtosis may be used best to illustrate the separativeness of the sedimentary environment.

From the data gathered on the Beaufort Inlet sediments, the lithologic and size variations in the bottom sediments showed a distinct conformity with the physical environments differentiated by the inlet's physical characteristics.

By comparing various statistical parameters, a marked distinction between the depositional environments was ascertained and again compared exactly to the inlet's physical environments.

REFERENCES CITED

Bruun, Per and Gerritsen, F., 1958, Stability of coastal inlets: Proc. Am. Soc. Civil Engineers, Paper 1644, 49 p.

Folk, R. L. and Ward, W. C., 1957, Brazos River bar: A study in the significance of grain size parameters: Jour. Sed. Petrology, v. 27, p. 3-26.

Inman, D. L., 1952, Measures for describing the size distribution of sediments: Jour. Sed. Petrology, v. 22, p. 125-145.

__________, and Chamberlain, T. K., 1955, Particle size distribution in nearshore sediments, _in_ Finding Ancient Shorelines: Tulsa, Okla., Soc. Econ. Paleontologist and Mineralogists, p. 106-126.

Krumbein, W. C. and Pettijohn, F. J., 1938, Manual of sedimentary petrography: New York, D. Appleton-Century Company, Incorporated, 549 p.

Passega, R., 1957, Texture as Characteristic of clastic deposition: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 1952-1983.

U. S. Congress, 1948, North Carolina shoreline, beach erosion study: House Doc. 763, 80th Cong., 2d Sess., 33 p.